ANALYZING RISK AND UNCERTAINTY FOR IMPROVING WATER DISTRIBUTION SYSTEM SECURITY FROM MALEVOLENT WATER SUPPLY CONTAMINATION EVENTS

A Thesis

by

JACOB MANUEL TORRES

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2008

Major Subject: Civil Engineering

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Approved by:

Co-Chairs of Committee,	Kelly Brumbelow
	Seth D. Guikema
Committee Members,	Carla Prater
Head of Department,	David V. Rosowsky

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ABSTRACT

Analyzing Risk and Uncertainty for Improving Water Distribution System Security from Malevolent Water Supply Contamination Events. (May 2008)

Jacob Manuel Torres, B.S., Texas A&M University

Co-Chairs of Advisory Committee: Dr. Kelly Brumbelow
Dr. Seth D. Guikema

Previous efforts to apply risk analysis for water distribution systems (WDS) have not typically included explicit hydraulic simulations in their methodologies. A risk classification scheme is here employed for identifying vulnerable WDS components subject to an intentional water contamination event. A Monte Carlo simulation is conducted including uncertain stochastic diurnal demand patterns, seasonal demand, initial storage tank levels, time of day of contamination initiation, duration of contamination event, and contaminant quantity.

An investigation is conducted on exposure sensitivities to the stochastic inputs and on mitigation measures for contaminant exposure reduction. Mitigation measures include topological modifications to the existing pipe network, valve installation, and an emergency purging system. Findings show that reasonable uncertainties in model inputs produce high variability in exposure levels. It is also shown that exposure level distributions experience noticeable sensitivities to population clusters within the contaminant spread area. The significant uncertainty in exposure patterns leads to greater resources needed for more effective mitigation.

DEDICATION

This thesis is dedicated to my family and friends

for their continuing support,

encouragement, and love in my

pursuit of a higher education.

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First and foremost, I want to thank my primary research advisor, Dr. Kelly Brumbelow, for his advice, guidance, and patience throughout my two years as an undergraduate researcher and graduate student. My knowledge, appreciation, and love for water resources engineering began with him. I express a sincere gratitude to my co-chair, Dr. Seth Guikema, for giving me confidence to believe in my ability to contribute to quality research. A warm thank you is also extended to Dr. Carla Prater for showing me the importance of bridging technical competence with policy.

Thank you to my good friend, Lufthansa, for being a valuable source of honest research advice. Thank you to the Zachry Department of Civil Engineering faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my sincere gratitude to the TAMUS – Louis Stokes Alliance for Minority Participation (LSAMP) Bridge to the Doctorate Fellowship for funding my graduate studies and research, and for making my pursuit of a Ph.D. a more reachable goal.

Thank you to my mother, Grace; two sisters, Marie and Amy; and grandparents, Baldemar and Maria, for their love and understanding of my intention to continue advanced studies. I share my deepest gratitude with Edith, my soon-to-be wife, for her unconditional support, encouragement, and love throughout my graduate studies. Finally, I want to thank my Lord and Savior Jesus Christ for giving me the strength, wisdom, and discipline to reach this academic milestone.

NOMENCLATURE

WDS	Water Distribution System
GIS	Geographic Information System
IRAM	Infrastructure Risk Analysis Model
HHM	Hierarchical Holographic Modeling
EPA	Environmental Protection Agency
AWWA	American Water Works Association
ASCE	American Society of Civil Engineers
WEF	Water Environment Federation
MCL	Maximum Contaminant Level
FBD	Functional Block Diagram
SCADA	Supervisory Control and Data Acquisition
WTP	Water Treatment Plan
PDF	Probability Density Function
EMS	Emergency Medical Service
NGO	Non-Governmental Organization
TRETS	Television, Radio, Email, Text, Siren
MC	Monte Carlo Simulation

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1. INTRODUCTION

Modern society is fortunate that successful contamination of water distribution systems is a rare event. However, the historical records on such accidents are too small for conventional statistical methods to produce reliable results for risk assessment. Therefore, probabilistic risk analysis (PRA) techniques are critical in estimating the frequencies of accidents in complex systems [1]. Water distribution systems are one of eight critical infrastructures defined in the report by the President's Commission on Critical Infrastructure Protection [2]. However, because water distribution system data for real cities contains sensitive information, it is necessary and understandable for it to remain confidential. Unfortunately, this poses a constraint on the research community, as results and methods cannot be shared and publicized. The procurement of water distribution data alone can prove to be quite arduous. Therefore, the development of a virtual city can be necessary for reasonable representations of key characteristics for actual cities. These characteristics include: timeline patterns of development, demographics, and municipal economics. One virtual city can serve as a "hub" for several multidisciplinary models based on virtual city data. The addition of larger cities will assist in forming a "library" of virtual cities for public domain usage and comparative development.

The need for reliable threat assessments for water supply infrastructures potentially subject to malevolent attacks has grown in the water distribution system

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This thesis follows the style of Reliability Engineering and System Safety.

(WDS) research community following 9/11. Therefore, the examination of smaller-scale systems is necessary for gaining a basic understanding on such national issues [3]. To address this need, Micropolis, a virtual city representing 5,000 residents has been developed. The key characteristics of Micropolis are contained within a geographic information system (GIS) framework. For the current research application, a few characteristics of interest include: pipe sizes, pipe lengths, pipe material, water demands, demand patterns, building populations, building types, and storage tank levels. In the present thesis, a vulnerability assessment is performed for a WDS in the event of a water supply contamination attack on Micropolis. A Monte Carlo simulation is then conducted and analyzed to examine uncertainties within critical WDS inputs. It is shown that an understanding of hydraulic uniqueness of water distribution systems is important for building robust risk models, performing vulnerability assessments, and developing emergency response programs. Knowing what direction water flows through pipes and how much water is used at any given time is vital for gaining reasonable estimates on contamination exposures.

Methods for improving mitigation, preparation, response, and recovery from WDS contamination events are further discussed. These include generalized vulnerability assessments, cost-effective mitigation measures, well coordinated preparation policies that involve all major emergency service groups, and the use of existing communication technologies for developing an efficient response plan. The importance of supplementing water supply contamination emergency planning with extended period simulation models is also discussed.

2. LITERATURE REVIEW

This section reviews only a portion of the diverse selection of literature available to the water distribution system community. The referenced literature in this section entails water distributions system security issues and suggested performance metrics. Background for Micropolis, the virtual city research application test bed, is also reviewed.

2.1. Vulnerability Assessments for Water Distribution Systems

The infrastructure risk analysis model (IRAM) [4] was developed for small community water supply and treatment systems in the United States. Its approach follows a holistic method for the modeling of a water infrastructure system's interconnectedness. This involves developing a detailed decomposition of a WDS, followed by a vulnerability analysis, whereby specific WDS components are assigned "access" and "exposure" factors. "Access" can be interpreted as any physical barrier, such as a fenced area or locked gate that hinders unwanted intrusion. "Exposure" can be a measure of public visibility or symbolic value. For example, a high-rise building located downtown has higher exposure and symbolic value than a single-family residential home located on the outskirts of town. The total vulnerability is then taken as the product of access and exposure [5] using the equation:

$$V = \sum_{i=1}^{n} \left(\alpha_i * \gamma_i \right) \qquad (2.1)$$

where V =system vulnerability; α_i=access factor of node i ranging from 0 (zero accessibility) to 1 (high accessibility); γ_i=exposure factor of node i ranging from 0 (zero exposure) to 1 (high exposure). This approach of conducting a vulnerability analysis to identify risks can be viewed as a risk classification scheme rather than a probabilistic risk analysis. This helps to provide the basis for prioritizing critical WDS components within the Micropolis virtual city.

Apostolakis and Lemon [3] recognize that society cannot afford the costs associated with absolute protection. They model infrastructures as interconnected digraphs and employ graph theory to help identify the candidate vulnerable scenarios. These scenarios are screened for susceptibility based on access controls, and then prioritized using multiattribute utility theory.

The Environmental Protection Agency (EPA) lists current practices for self-assessment of small water systems [6]. They include:

- Inventory of small water system critical components.
- General questions about the whole system such as the existence of an emergency response plan, access to critical components, external lighting, patrol, warning signs, and operation and management. Action plans are required for defective areas.

- General questions about water sources, treatment plants, distribution, personnel, information, storage, computers, controls, maps, and public relations. Action plans are required for defective areas.
- Prioritization of needed actions.
- Emergency contact lists.
- Threat identification checklists.
- Certification of assessment completion.

Grigg [7] adds to this approach by suggesting a comprehensive program to develop water system security indicators. The measurement of security indicators, threat, vulnerability, and consequence, are applied to the lowest system levels (such as a water main) which then become aggregated [7]. Though not all of these indicators can be quantified, they can be conceptualized using systems theory. This at least helps to outline the problem so that the focus can be set on areas in need of security improvement.

Bristow and Brumbelow [8] construct probability distributions to measure the time delay between sensing and response in water contamination events. They structure the delay between sensing and response into five distinct phases. These include: warning transmission, contamination verification, drafting of warning message, warning broadcast, and warning compliance. The entire response process is modeled using a Monte Carlo approach to determine probability distributions for response delays. This is supplemented by the use of thirteen case studies in which actual cities had clearly documented event timelines for “contaminant verification” and “drafting of warning message" delays. These timelines provide the justification for the simulation time used for the contamination event modeled in the present thesis.

2.2. A Brief History of Micropolis

Micropolis is the first entry into a soon to be "library" of virtual cities. It currently exists in both GIS and EPANet frameworks as shown in Fig. 2.1. A GIS allows layers of spatial data to overlay onto a map for the viewing of spatial relationships among various layers of data. This environment was used to create the city of Micropolis. EPANet was used to model the Micropolis WDS. It is a hydraulic and water quality modeling program developed by the U.S. Environmental Protection Agency [9]. It allows for a time series simulation of water distribution systems including water quality parameters. Pipe leak detection, water supply contamination, and fire spread models have already been developed for Micropolis, while telecommunication and power distribution system models are currently in progress.

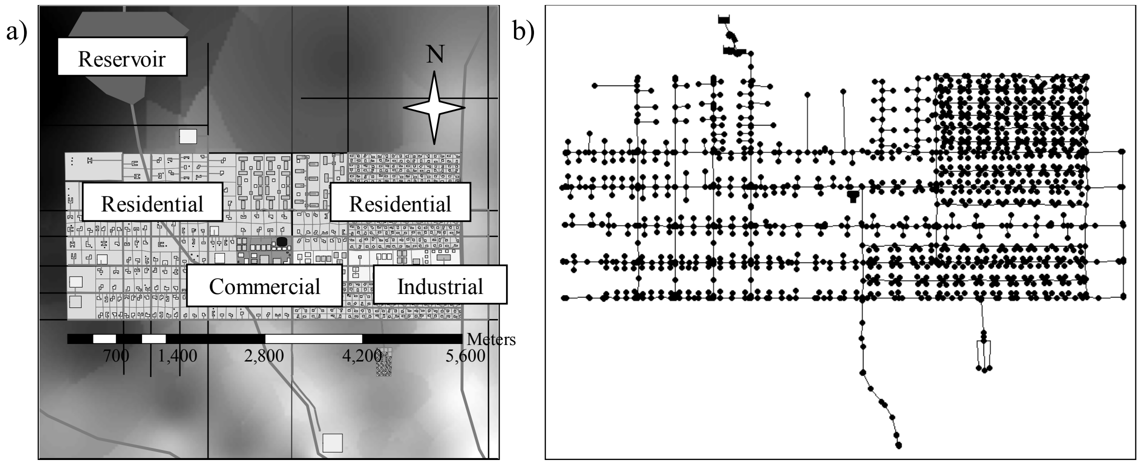


Fig. 2.1. Micropolis in (a) GIS and (b) EPANet frameworks.

A selection of the primary physical and operational characteristics of Micropolis include a comprehensive building map, designated property lots, residential, commercial, and industrial zones, pipe and road networks, one elevated storage tank, one water treatment plant, one wastewater treatment plant, diurnal water demand patterns for each user, pump operation schedules, an elevation grid, and an electric power distribution system. The city's main source of water arrives from groundwater wells and a surface reservoir located to the north.

Micropolis was developed using a historical development timeline to incorporate as many attributes of a true city as possible. For example, it was assumed that Micropolis was first settled in the 1850s, and continued to expand with time. One key reason for applying a timeline pattern of development was for the incorporation of various pipe material used throughout time. During the early 1900s most pipes were of cast iron material. Micropolis reflects this circumstance in its oldest area, the commercial zone. Pipes installed in the 1950s were mainly of asbestos cement, and pipes installed in the 1980s were of ductile iron. These pipes are included in the commercial and industrial zones. Micropolis also incorporates the idiosyncrasies of pipe material topology resulting from irregular replacement. For example, a break in an old pipe is replaced with the dominant pipe material at time of replacement. Variations in pipe material reflect variations in pipe roughness factors. This plays an important role in hydraulic behavior and how a WDS functions.

2.3. Water Security and Emergency Response

Executive Order 13010 [10] and Presidential Decision Directive [2] identified water supply systems as one of eight critical infrastructures and established the need for its increased protection. Though the probability of carrying out successful contamination events on U.S. water supplies is small, the possibility remains real. Previous attacks and attempted attacks on U.S. water supplies have proven this fact, as shown in Table 2.1 [11]. This account is in addition to a large number of deliberate acts of simple pranks and vandalism that go unrecorded by utilities because of fear of encouraging copycat events or public overreaction [12].

Table 2.1. Previous water supply attacks and attempted attacks [11].

Year	Assailant(s)	Event	Agent
1984	religious cult	Contaminated municipal drinking water storage tank in Oregon.	salmonella
2001	Bin Laden operative	Possible plot to contaminate water supplies in twenty-eight cities. Plan later determined not to be credible.	—
2002	Moroccans	Developed plot to contaminate water pipes leading to U.S. Embassy in Rome	cyanide
2002	Al Qaeda	Arrested U.S. residents with documents on how to contaminate water supplies.	—
2003	Iraqi operatives	Poisoned U.S. food & water supplies.	botulinum toxin
N/A	religious cult	Acquired drums of cyanide to dump cyanide into Minneapolis reservoirs.	cyanide

Though much literature on mitigation, preparedness, response, and recovery is devoted to natural disasters, there has been an increased amount on water distribution system contamination events within the current decade. The American Water Works Association (AWWA), the American Society of Civil Engineers (ASCE), and the Water Environment Federation (WEF) have recently drafted a joint standard for trial use on guidelines for improving the physical security for facilities used in potable water source, treatment, and distribution systems [13].

3. METHODOLOGY

This section develops the model for assessing risks due to an intentional arsenic contamination event. Arsenic trioxide has been selected as the case study because of its ready accessibility and potential to frighten the public. Arsenic already poses a threat to certain U.S. cities that rely on groundwater sources; therefore many citizens know enough to perceive arsenic in drinking water as harmful. This knowledge gives the intruder a basis for using arsenic as their contaminant of choice, knowing very well the fear that would result upon public notification.

Risk classification and uncertainty propagation techniques are here applied for identifying WDS vulnerabilities and for quantifying the probability density functions for population exposures above the maximum contaminant level (MCL). A base-case contamination simulation is presented with investigations on arsenic exposure levels and proposed mitigation strategies. This methodology has been divided into five distinct phases as shown in Fig. 3.1.

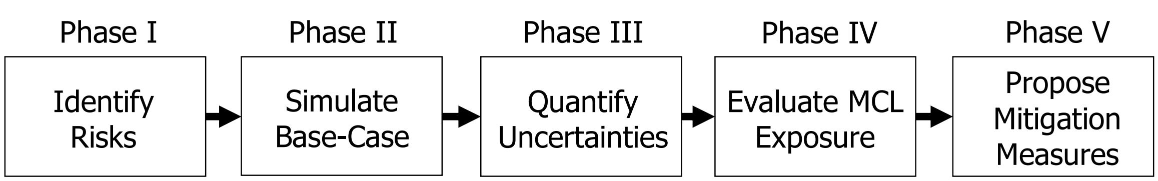


Fig. 3.1. Methodology.

Phase I entails the classification of WDS risks for all water users and prioritizing each user's vulnerability to contamination based on the access and exposure factors previously mentioned. Phase II begins with analyzing the highest ranked vulnerability within the WDS obtained from Phase I and establishes a base-case contamination scenario. This includes a time series simulation using EPANet for monitoring the spatial extent to which the contaminant spreads. This is important for gaining a basic understanding on how the hydraulic behavior of the WDS affects contamination exposure. Phase III applies uncertainty propagation techniques for quantifying the MCL exposure uncertainties in the model output, given the assessed uncertainties in the model inputs. Phase IV conducts an additional evaluation on variability contained in the results from Phase III. Finally, Phase V proposes and reviews outcomes for several mitigation strategies.

4. ANALYSIS AND RESULTS

For the present thesis, a WDS decomposition was performed as in Ezell et al. [5] using hierarchical holographic modeling (HHM) [14]. Fig. 4.1 presents the decomposition as it applies to Micropolis using HHM. This decomposition was needed only to help structure the critical components within the Micropolis WDS.

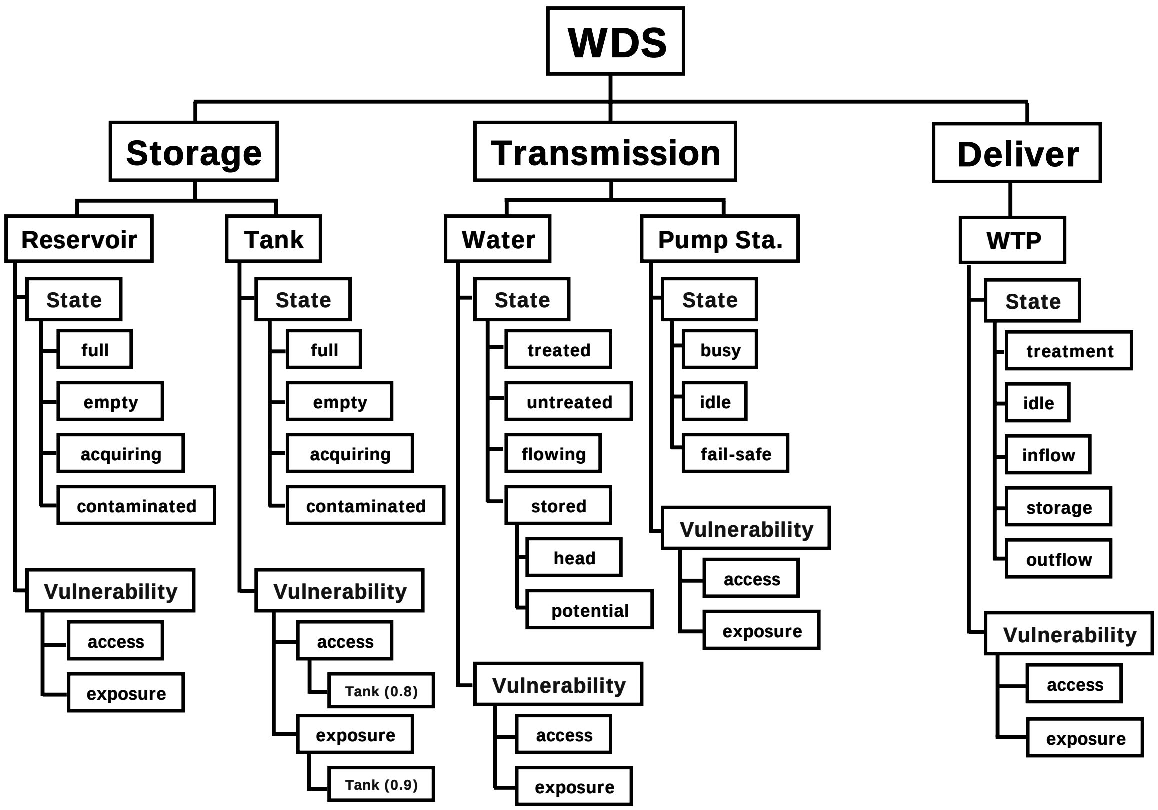


Fig. 4.1. HHM of Micropolis WDS (method adapted from Ezell [5]).

4.1. Phase I – Risk Classification

The underlying basis for the method used in the risk classification scheme revolves around three axioms based on Ezell et al [5]. The first axiom states that the primary goal of the intruder is to harm as many people as possible by way of water contamination. The second axiom states that contamination vulnerability is proportional to contamination risk. To support this claim, risk of an adversary attack can be taken as the product of consequence, threat, and vulnerability as shown in Equation (4.1) [15]:

$$R = C * T * V \tag{4.1}$$

where R = risk; C = consequences measured by loss of life, economic impact, loss of public confidence, or other metrics; T = threats characterized by their mean and likelihood of occurrence and their potential to disrupt systems; and V = vulnerability to the threat that would cause degradation or system failure. Therefore, within reason, it can be concluded that the more vulnerable a resource is to a disaster, the more at risk that resource is to attack by an adversary. The third axiom follows that system vulnerability is a function of component access and exposure [5]. These axioms provide the basis for ranking WDS risks in Micropolis that are subject to a contamination event.

Determination of access and exposure factors for assessing vulnerability was done using a GIS in which 700 demand nodes and critical WDS components were assigned access and exposure factors based on expert judgment, while maintaining the first axiom. By applying Equation (2.1), vulnerability scores were computed for each user node and other critical WDS components such as the water treatment plant, storage tank, and pump station. These scores were then used to generate a Vulnerability Surface Map as shown in Fig. 4.2. This figure serves as a "spatial tool" for identifying the range of vulnerabilities to a contamination event within the Micropolis WDS.

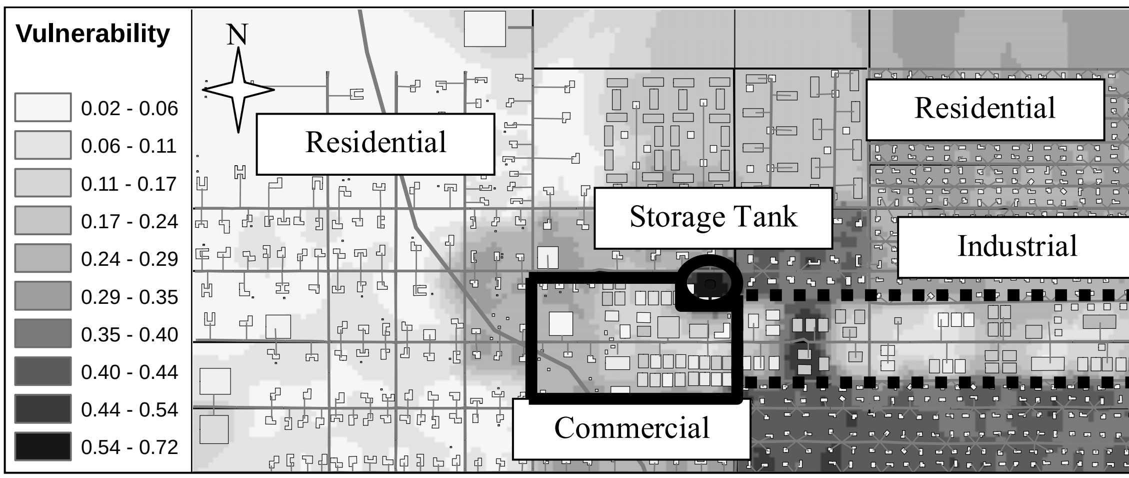


Fig. 4.2. Vulnerability surface map.

All nodes contained in the solid box represent commercial users, while all nodes contained in the hatched box represent industrial users. The remaining nodes represent residential users, with a few representing schools, shops, and churches. As shown in Fig. 4.2, the vulnerability ranges from 0.02 to 0.72. When considering risk in terms of access and exposure, the western and eastern portions of Micropolis share similar exposure factors. However, they differ in terms of access. Micropolis was developed in such a way that the western portion is considered to be the more recent development with more robust home security features than the east. Based on the Vulnerability

Surface Map, nodes near the outer edges of the city limits are less vulnerable due to lower exposure levels. As one nears the town center (commercial zone), exposure increases, therefore this area experiences higher vulnerability. The town center is also much older, as it was developed during the early phases of Micropolis's "history." The northeastern portion of the city is also an older residential area, and is poorly maintained; therefore access scores are significantly higher in this area. In all areas, security systems for homes and facilities (including the water tower) are assumed to be no more complex than simple door and gate locking mechanisms, as is typical for small U.S. towns.

According to the Vulnerability Surface Map, the node identified as the one having the highest vulnerability is the node in the center of town contained within the oval. It was rated with an access and exposure factor of 0.8 and 0.9, respectively. This yields a component vulnerability score of 0.72. This node represents the city's elevated storage tank (water tower). The highly exposed storage tank not only lacks reliable security, but also satisfies the three axioms, making it a prime target for initiating an intentional contamination event.

Upon identification of the most vulnerable WDS component susceptible to contamination, it is useful to model a base-case contamination event using the water tower as the prime intrusion point. To begin, a functional block diagram (FBD) is drawn to encapsulate the contamination event process. A FBD for a successful contamination event can become quite complex due to the large scale of interconnectedness for typical WDS mechanical functions. Therefore a simplified FBD for a WDS contamination event can be developed that would only account for physical systems in terms of detection and security, and policies such as response and recovery. Fig. 4.3 illustrates this FBD for a successful contamination event

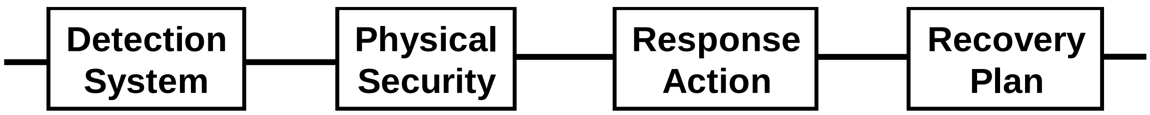


Fig. 4.3. Functional block diagram.

Note that this FBD is in terms of a series of mitigating systems that would need to fail in order for potentially harmful exposures to occur. This is slightly different from conventional FBDs that are usually expressed in terms of mechanical functions, such as pipes, generators, pumps, etc. The "detection system" can represent the existence of a supervisory, control, and data acquisition (SCADA) system and/or real-time chemical tracking sensors. In a small town like Micropolis, the cost of such a detection system might be prohibitively high. "Physical security" can represent surveillance systems, wall barriers, barbed wire fences, locks, and alarms. As stated earlier, the water tower is assumed to be guarded by nothing more than a locked gate. "Response action" can represent the methods used by a city, such as valve closures, for reducing further spread. "Recovery plan" can include not only recovery policies to purge the system of contaminants and restore order, but the abilities of water users to regain trust as a result of their exposure to WDS disruption.

Fig. 4.4 presents the fault tree assuming independence and no external events. The Boolean polynomial, $T = A + B + C + D$, is obtained. This fault tree simply confirms the series behavior in that all mitigating systems must function to prevent a successful contamination event. Upon reaching this conclusion, the methodology is resumed to simulate a base-case contamination event using the water tower as the prime intrusion point.

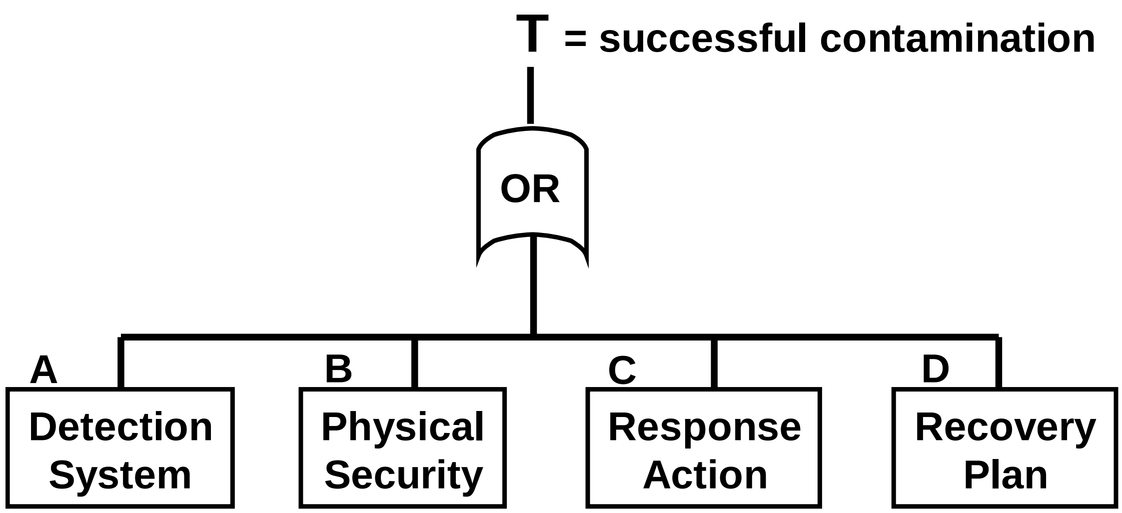


Fig. 4.4. Fault tree.

4.2. Phase II – Simulation of a Base-Case Contamination Event

To aid in understanding the hydraulic model simulations, a brief discussion of pressure conduit fluid mechanics is useful. In pressure conduit fluid mechanics there are two important governing equations. The conservation of mass (or continuity) equation states that mass or fluid must be conserved as the net sum of inflows and outflows at a point. The energy equation provides the basis for estimating energy change along a flowpath. For any given point, energy (usually called “head” in civil engineering applications) exists in three forms. These forms include, potential energy (or elevation head) indicated as Z_1 in Fig. 4.5, pressure head indicated as P_1/γ, and kinetic energy (or velocity head) indicated as $V_1^2/2g$.

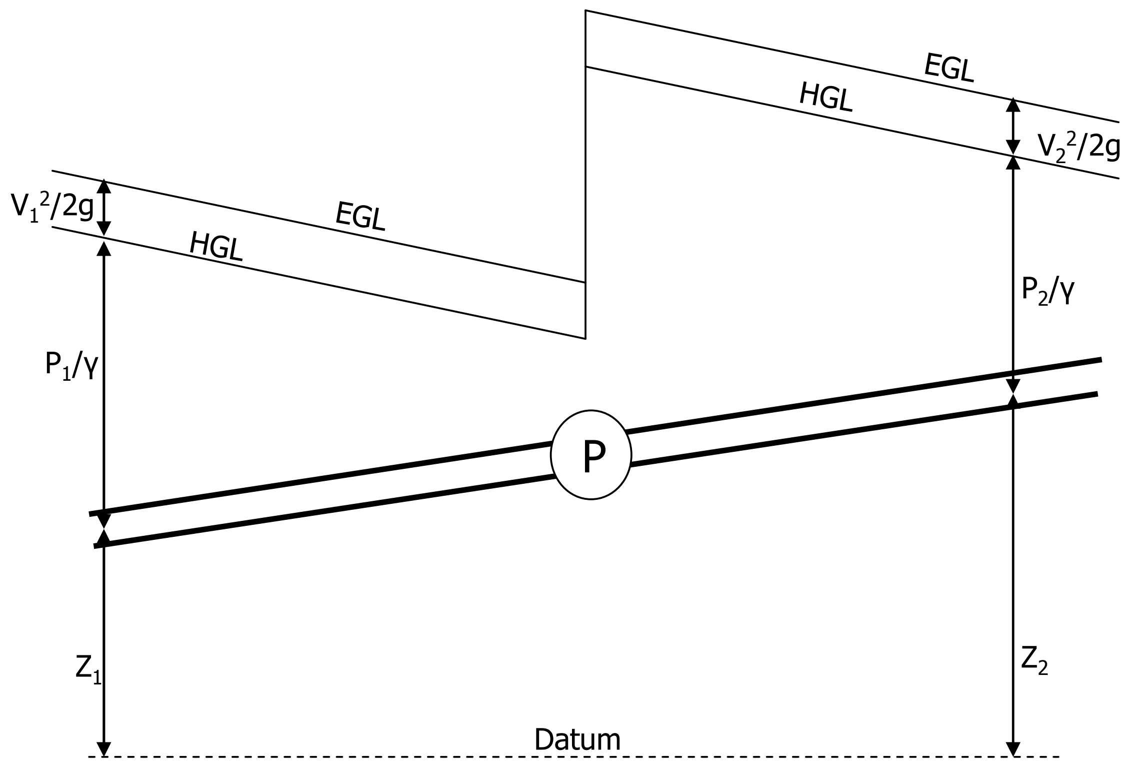


Fig. 4.5. Energy equation for pipeline flow [16].

The "P" in Fig. 4.5 represents a pump. A pump is used to add energy to the flow. HGL and EGL represent the hydraulic grade line and energy grade line, respectively. The headloss (energy loss) is equal to the slope of the energy grade line. As fluid flows from high head to low head, energy is lost due to friction in pipe walls, pipe bends, pipe entrance geometry, pipe exit geometry, valves, etc. The energy equation between two points along a pipe can be expressed as:

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = Z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + H_L - E_p \tag{4.2}$$

where H_L = headloss and E_p = energy added by the pump. A water distribution system can be described with a system of continuity and energy equations, which can be solved for flows in its pipes and pressures at its nodes. The EPANet software determines this solution using the "gradient" algorithm [17]. Understanding that headloss, elevation, pressure, and velocity gradients are responsible for pressurized conduit fluid flow behavior is important because the physics of fluid flow in pipes partially governs population exposures to contamination. Risk models that do not account for temporal and spatial patterns in flow do not provide detailed, accurate estimates of population exposures.

Before running the simulation for a base-case contamination event, a contamination scenario is first established. As stated previously, the specific contaminant to be modeled is arsenic trioxide, As_2O_3. It should be noted that pure arsenic is not water soluble, although many arsenic compounds may be slightly soluble. This thesis focuses on arsenic exposure for users who receive arsenic concentrations greater than the MCL of 0.01 mg/L [18]. The MCL is the highest level of a contaminant that is allowed in drinking water, set by the EPA with authority granted to them by the Safe Drinking Water Act of 1974. The MCL threshold for arsenic is very low, and in most cases, probably would not have significant health consequences, unless chronic exposure is considered (which it is not). Arsenic levels greater than the MCL already exist in human urine, blood, hair, finger nails, and toe nails [19]. However, what this thesis attempts to quantify is contamination vulnerability and capability. There is still reason to believe that arsenic levels equal to or exceeding the MCL threshold would result in mass fear and loss of public confidence in the water supply infrastructure once news of this became public. The number of people exposed above the arsenic MCL is measured in order to illustrate the methodology and usefulness of virtual cities, but other thresholds may be adopted as appropriate for particular problems.

Decay of arsenic trioxide is approximated as a first-order reaction:

$$\ln\left(\frac{C}{C_o}\right) = -kt \tag{4.3}$$

where C = concentration of the reactant at any time t, C_o = initial concentration of reactant, $-k$ = rate constant indicating decay, t = time elapsed. The first-order approximation is justified with the assumption that existing chlorine residuals within the pipe network are much higher and more widespread than the arsenic concentrations being inserted. It is assumed that the arsenic inserted into the system would not react with chlorine in such a way that would cause significant drops in chlorine concentrations for the entire WDS. Therefore, there are no significant changes in chlorine concentration levels as a result of its reaction to arsenic. If this is not the case, it would be necessary to model arsenic as a second-order reaction decay.

All contamination events are simulated for a 72-hour duration. This duration is meant to reflect total response time for a city such as Micropolis. It is assumed that at this time the contamination event would be realized and efforts would be made by the city to isolate the contaminant by way of valve closures and other methods for isolating the spread. It is also assumed at this time that public notification would be made concerning the event and further consumption of tainted water would cease. This 72-hour period was inspired by Bristow and Brumbelow [9], wherein thirteen case studies clearly documented response timelines for actual water contamination events.

The base-case contamination scenario consists of 45 kg (≈ 100 lbs) of arsenic inserted at the tank, beginning at 12:00 a.m., with an initial storage tank level of 33.5 meters (110 ft). The time of event occurrence is within the September through May time frame. This time frame indicates that water demands for all schools will be considered. The hydraulic and water quality simulation of the pipe network is executed using EPANet for a total duration of 72 hours. Fig. 4.6 presents maps of contaminant concentration in the system at times after insertion for 6 hours, 18 hours, 48 hours, and 72 hours. The legend includes the MCL threshold of 0.01 mg/L. It is clear that many users experience exposure levels much greater than this.

As shown in Fig. 4.6, certain users experience arsenic exposures greater than 0.2 mg/L and 2.0 mg/L at various times. Arsenic exposures in drinking water for concentrations ranging between 0.17 to 0.8 ppm (0.17 mg/L to 0.8 mg/L) are capable of causing Blackfoot disease, which is endemic in certain developing countries [20]. Arsenic ingestion through water such as this can also have serious health effects on the human cardiovascular system [21]. According to Fennel et al. [22] and Goldsmith et al. [23], both acute and chronic arsenic exposure can also cause altered myocardial depolarization and cardiac arrhythmias that may lead to heart failure (qtd. in [21]). For the present thesis, only estimates of the number of people exposed above the MCL are discussed.

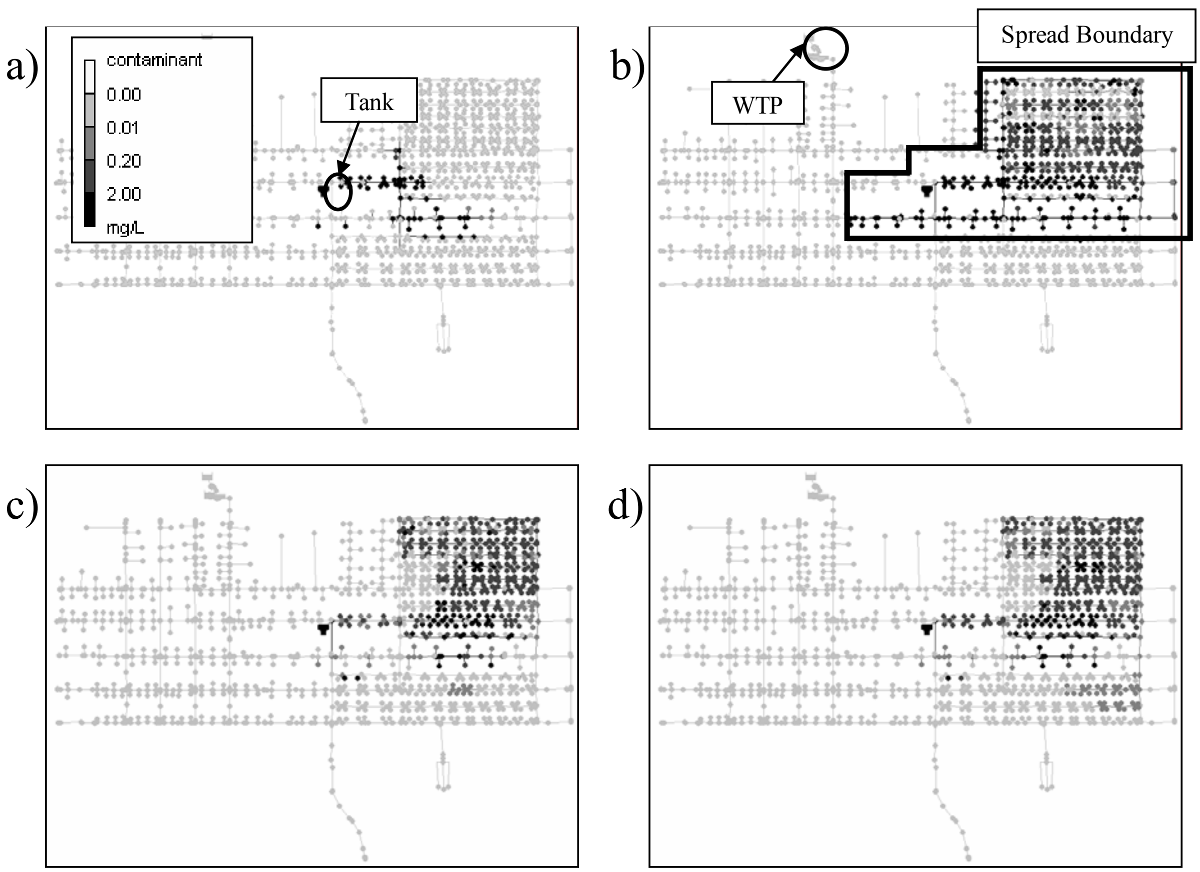


Fig. 4.6. Simulation for (a) 6 hours, (b) 18 hours, (c) 48 hours, and (d) 72 hours.

The purpose for modeling a base-case contamination event is to assess the spatial extent of the contamination spread. Fig. 4.6 shows that only users who receive water that has passed through the storage tank receive arsenic exposure. These residents are enclosed in the spread boundary polygon in Fig. 4.6(b). All other users get their water directly from the water treatment plant (WTP). Conventional wisdom may have led one to believe that the spread should have occurred in a concentric fashion. However, as Fig. 4.6 shows, this is not the case. Taking into account daily demand patterns for each user, pump operations, and flow directions play an important role in how the contamination spread behaves.

4.3. Phase III – Quantify Uncertainties

Uncertainty propagation consists of methods for quantifying uncertainties in the model output that are induced by the uncertainties in the model inputs [24]. For the given virtual water distribution model, it is shown how Monte Carlo simulations can be used to gain insights into the magnitudes of uncertainty in population exposures from a malevolent water supply contamination attack.

4.3.1. Uncertainties in Model Inputs

Monte Carlo simulations were used for uncertainty quantification and were implemented in a Visual Basic code linked to the EPANet Toolkit for iterative hydraulic simulations. Uncertainties are modeled for six inputs believed to carry the greatest impact on contaminant spread behavior. They include uncertainties in daily demand, initial storage tank levels, seasonal demand, time of initiation for contamination event, duration of arsenic intrusion, and quantity of contaminant inserted at the tank. Three of these inputs are modeled as lognormal distributions. Research shows that lognormal distributions are useful for representing non-negative and positively skewed physical quantities [24]. The probability distribution for each input is discussed.

To explain how uncertainties in daily demands are modeled, it is necessary to provide a brief discussion of the EPANet interface and how it handles demand information. In EPANet, a “base demand” is set for each user based on zone type (residential, commercial, industrial) and population. This “base demand” represents the average amount of water consumed in a 24 hour period. Because EPANet is capable of modeling hourly time increments, hourly (actual) demands can also be defined. To do this, daily demands for a single user are divided into 24 time periods, with each period containing a “multiplier” that is specified by the program user. It is referred to as a “multiplier” because EPANet multiplies this factor by the “base demand” to compute the actual demand for that hour. The sequence of multipliers for a 24 hour time period forms a daily demand pattern. The process of setting base demands, multipliers, and demand patterns is completed for all user nodes before any modeling takes place. These are considered to be “fixed” multipliers and demand patterns.

For modeling uncertainty in daily demands, a normal distribution was applied to each hourly multiplier value for all users. That is, each of the 24 multiplier values possesses its own distribution. If the model is to account for uncertainty in hourly demands using EPANet, then the uncertainty should lie in the hourly multipliers, not the base demand. The hourly demand distribution featured in Fig. 4.7 models the demand uncertainty for the 1st time period for a commercial restaurant. It is modeled as a Normal (0.2, 0.05) distribution. With five different patterns (residential, industrial, and three forms of commercial) and 24 time periods for each pattern, there are actually 120 different normal distributions used in the Monte Carlo analysis for accounting for stochastic daily demands. Fig. 4.7 presents only a sample distribution for a single multiplier.

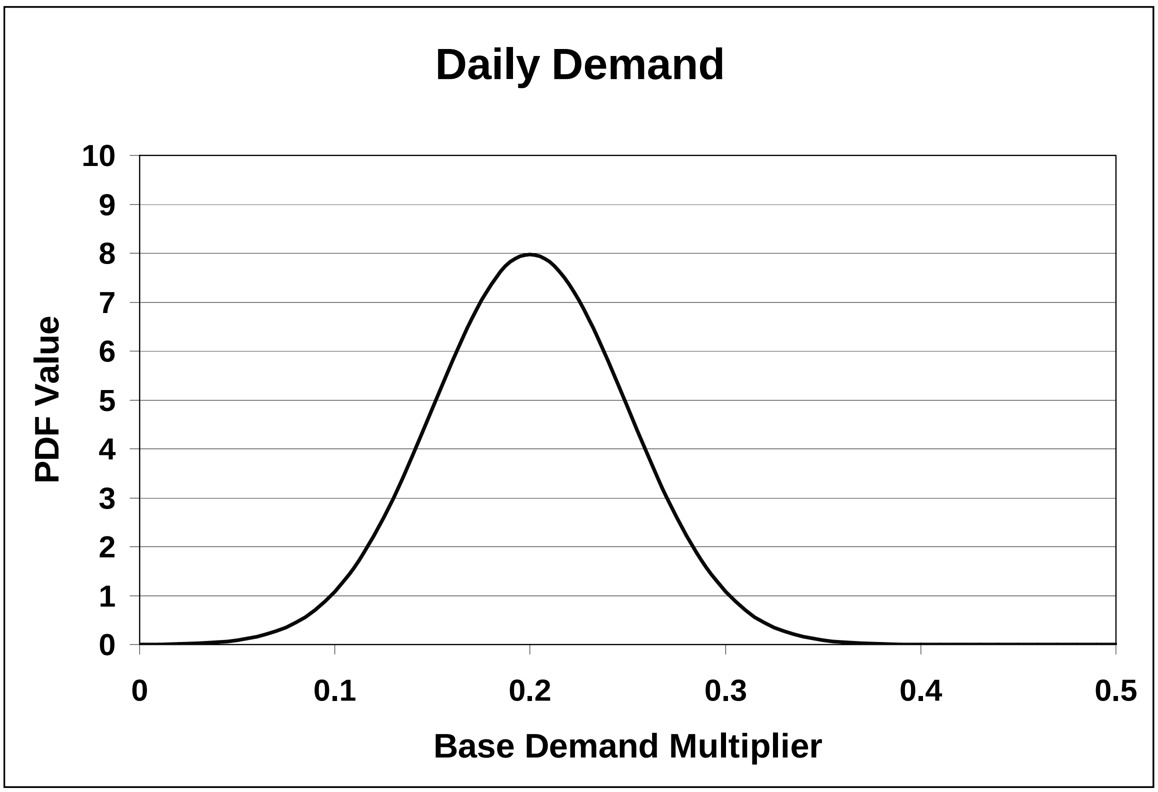


Fig. 4.7. Accounting for uncertainty in daily demand.

The mean and standard deviation for all demand distributions depend on their corresponding "fixed" multipliers. For a given time period, the fixed multiplier is used as the mean for its distribution with its standard deviation taken as 0.25*mean. This is represented in Fig. 4.8.

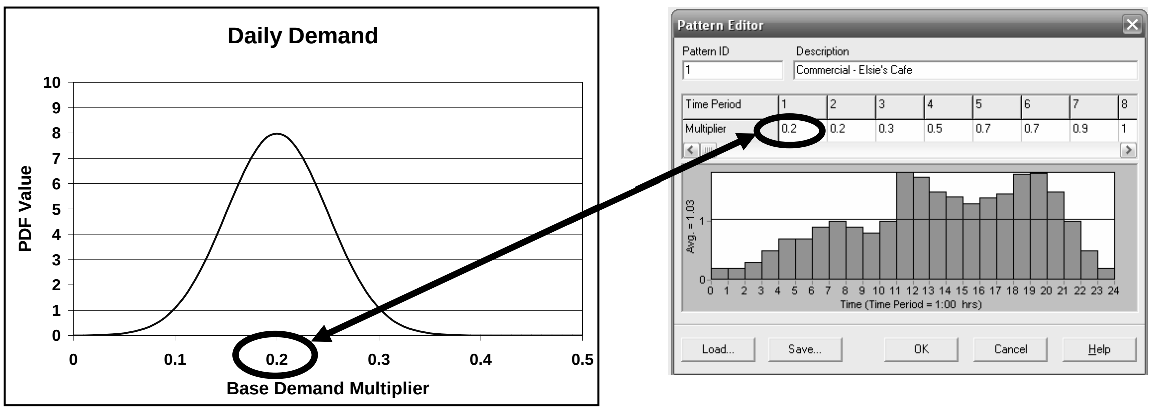


Fig. 4.8. Relating demand distributions with demand multipliers.

The advantage of applying distributions to each multiplier is that it allows the shape of the fixed (original) pattern to be maintained while making slight fluctuations in the individual multipliers. Fig. 4.9 illustrates this notion. Fig. 4.9(a) is the fixed pattern. Figs. 4.9(b), 4.9(c), and 4.9(d) are three realizations of the stochastic pattern that occur when a normal distribution is applied to each multiplier. It can be seen that individual multipliers vary, but the overall demand pattern shape for the restaurant is maintained. This is important because demand pattern shapes for specific users do not vary greatly. For example, the restaurant depicted in Figs. 4.7, 4.8 and 4.9 will almost always have demand peaks at breakfast, lunch, and dinner hours.

a) b) c) d)

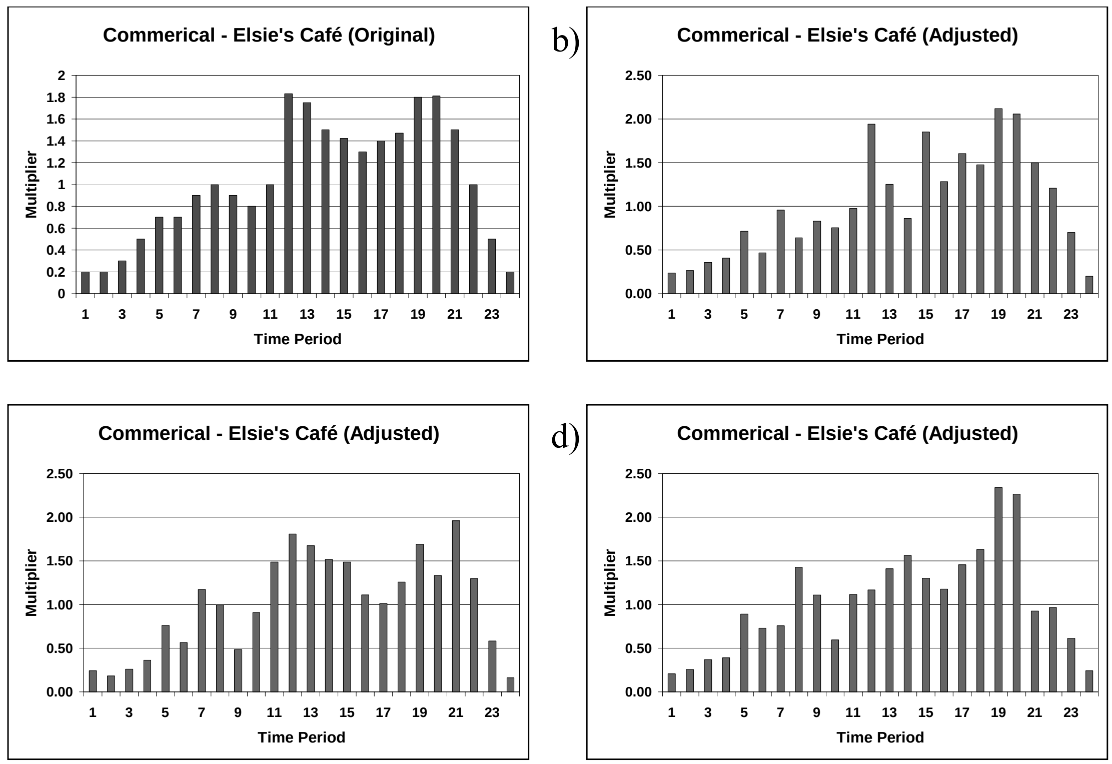


Fig. 4.9. Varying demand multipliers while maintaining pattern shape.

The initial level for the storage tank was modeled as a Lognormal (4.693, 0.016) distribution. Taking the exponential transform of the raw data set results in a mean, μ = 33.27 m (109.15 ft) and standard deviation, σ = 0.54 m (1.77 ft) as shown in Fig. 4.10. These values are based on the operational and hydraulic characteristics of the Micropolis WDS, which would typically attempt to have a relatively full tank in the early morning hours of the day; hence the relatively small standard deviation. This reasoning is demonstrated by a plot in Fig. 4.11 which illustrates tank levels versus time from a deterministic simulation showing that the tank levels generally repeat every twenty-four hours.

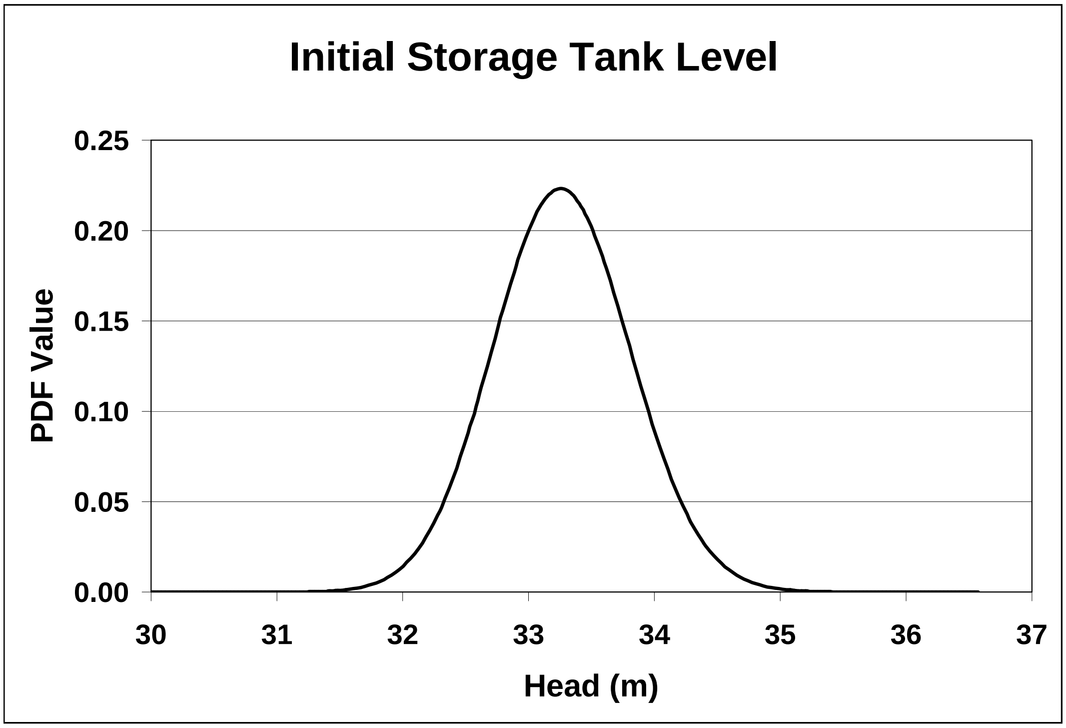


Fig. 4.10. Accounting for uncertainty in tank level.

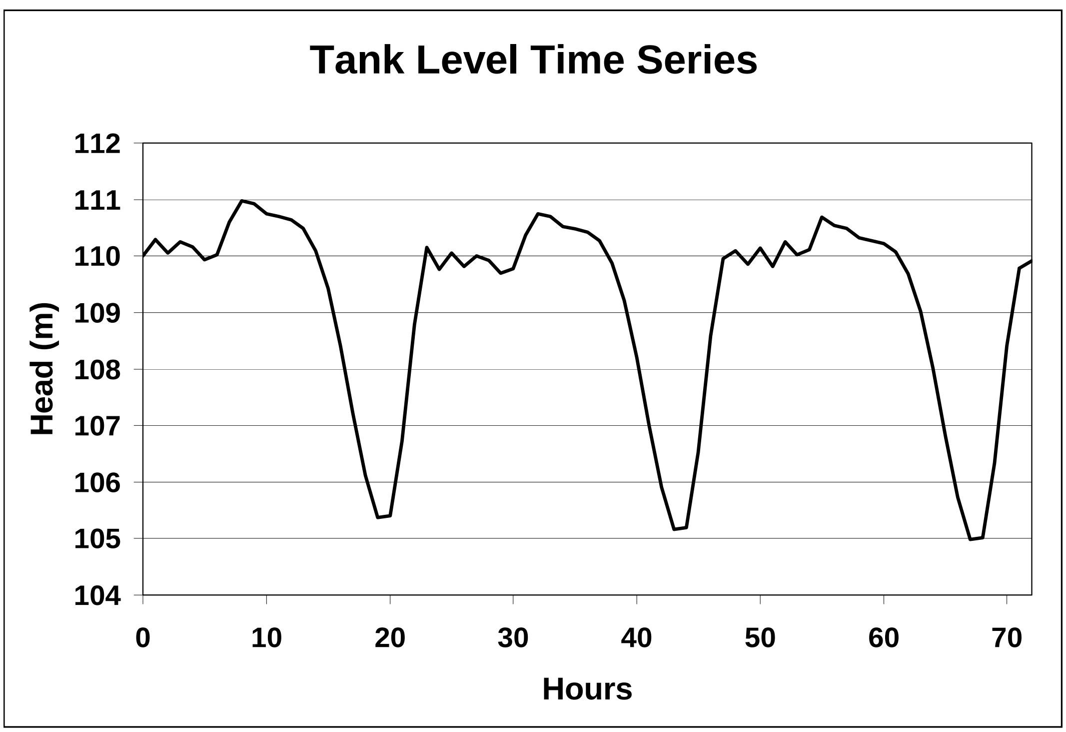


Fig. 4.11. Tank level time series.

In the case of Micropolis, seasonal demand patterns are driven principally by whether or not schools are in session. For a town such as Micropolis, they are the only users whose demands vary significantly within a 12 month period. It is assumed that schools are in session for 9 months of the year, and water use is negligible at the schools in the other 3 months. Applying Fig. 4.12, if a generated uniform random number (values of zero to one) is greater than 0.75, then a zero demand is assigned to all schools.

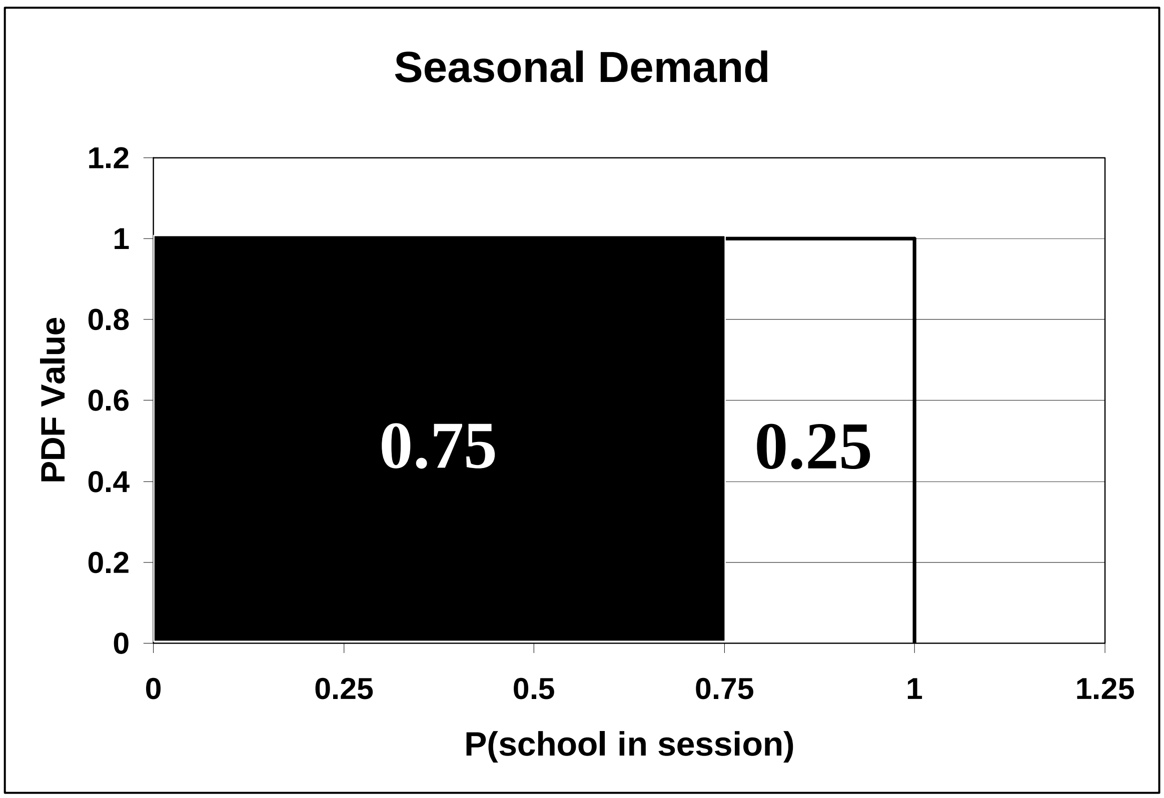


Fig. 4.12. Accounting for uncertainty in seasonal demand.

Because it is most likely for the contamination event to take place in early morning or late at night, the Beta (0.5, 0.5) is most attractive for determining when the contamination event is initiated. This distribution is shown in Fig. 4.13.

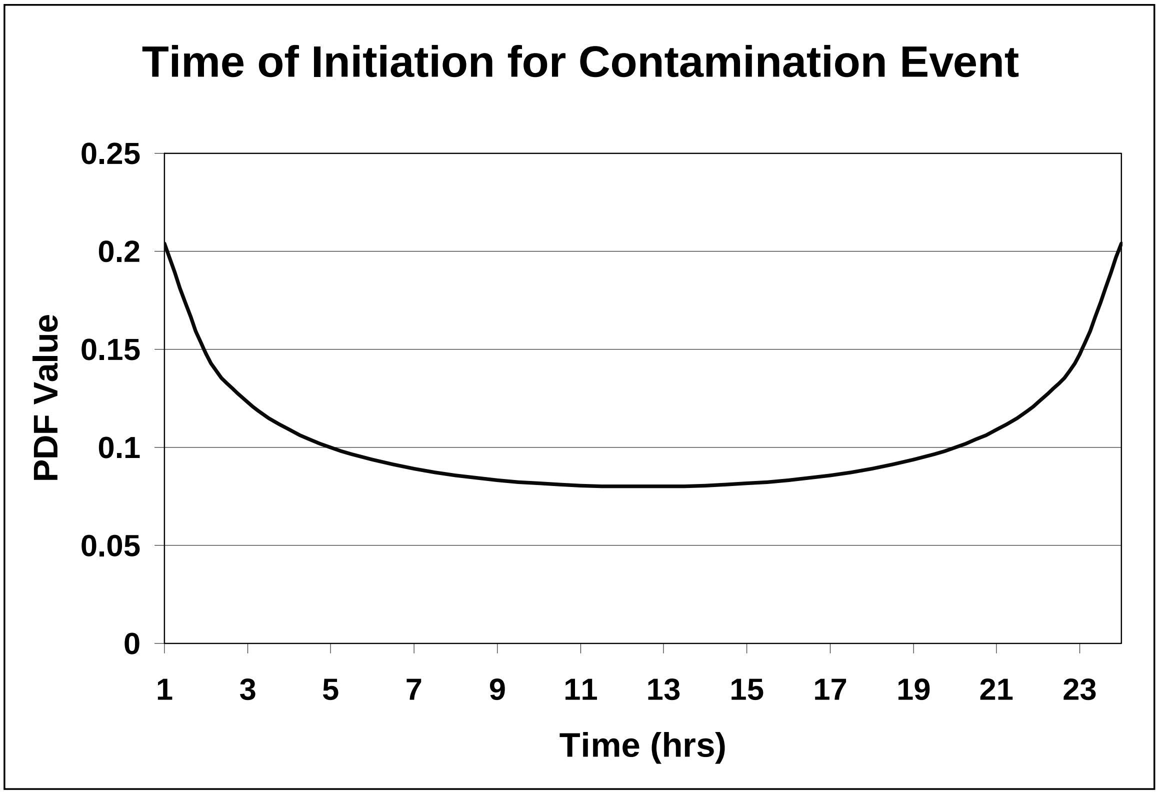


Fig. 4.13. Accounting for uncertainty in time for which contamination event is initiated.

Fig. 4.14 represents the amount of time required by the intruder to complete the arsenic contamination task. Once an event initiation time is derived from the Beta (0.5, 0.5) distribution, Fig. 4.14 is then used to "widen" the intrusion duration required by the intruder. This lognormal distribution assumes a mean, $\mu = 0.672$ and a standard deviation, σ = 0.642. Taking the exponential transform of the raw data set results in a μ = 2.2 hours and σ = 1.91 hours.

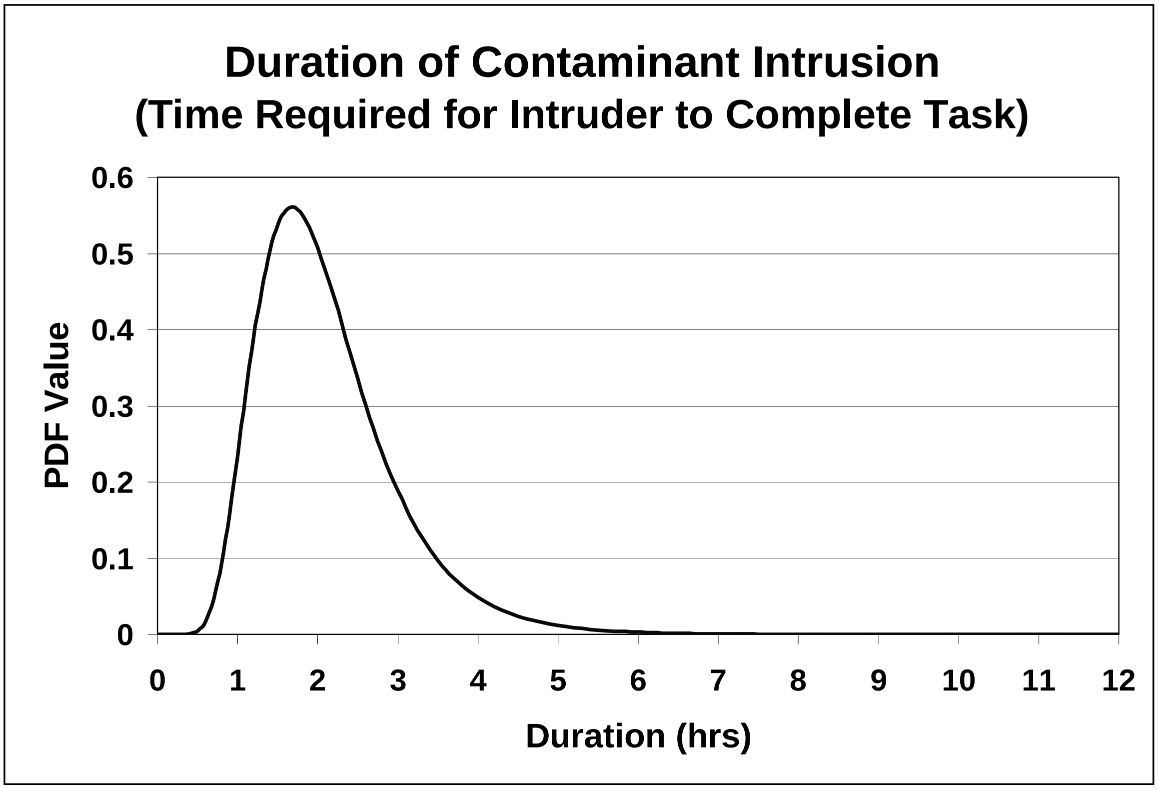


Fig. 4.14. Accounting for uncertainty in duration of contaminant intrusion.

When considering the amount of arsenic inserted at the tank, EPANet allows for different hourly quantities for a given "base quantity," similar to that just mentioned for demand patterns. Therefore, a lognormal distribution was modeled for a base flux of 45 kg/hr (≈ 100 lbs/hr). This was a reasonable amount to assume for one adult of medium build to carry. The hourly quantity is then varied according to randomly adjusted multipliers for each time period. The lognormal distribution for these multipliers assumes a mean, μ = -0.168 and a standard deviation, σ = 0.642 as shown in Fig. 4.15. Because there is much uncertainty in how much arsenic is actually used, the standard deviation was purposely chosen to be quite high. This distribution implies that the arsenic quantity becomes less attractive to the intruder for greater amounts of arsenic used. Greater amounts could require multiple trips, multiple people, and longer time to accomplish the task, which would result in a higher probability of being caught.

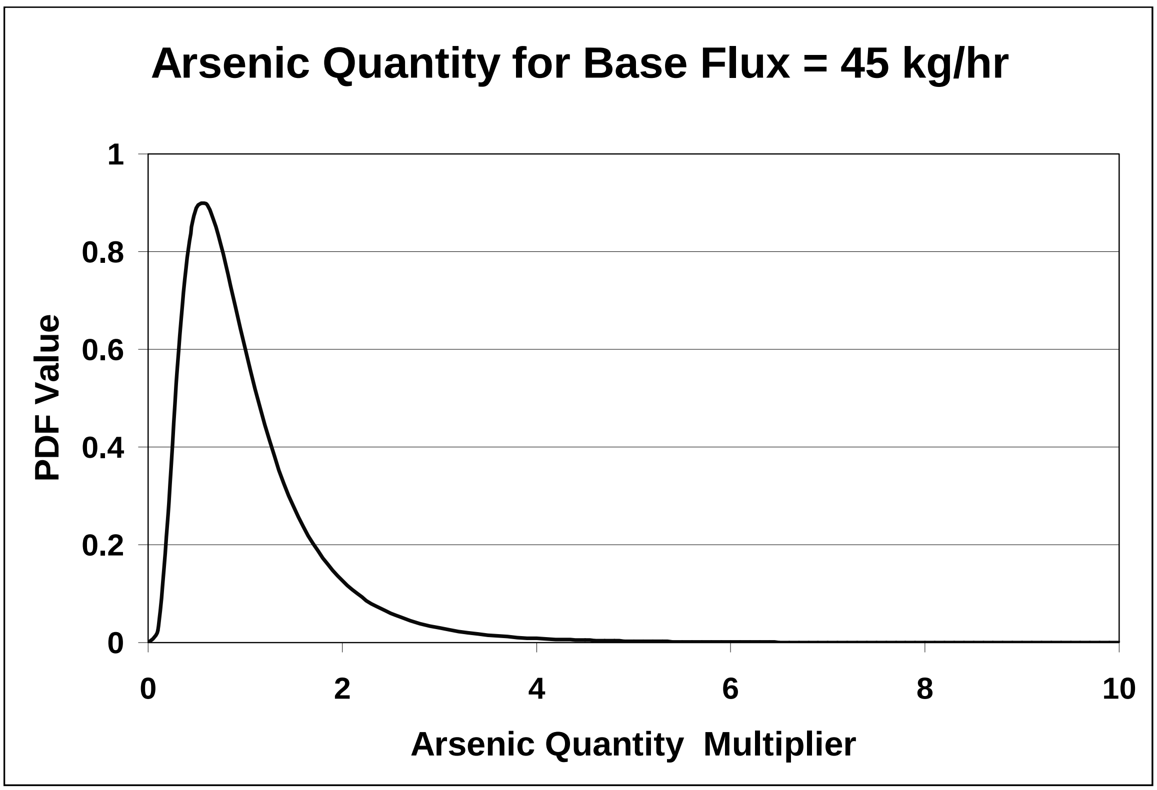


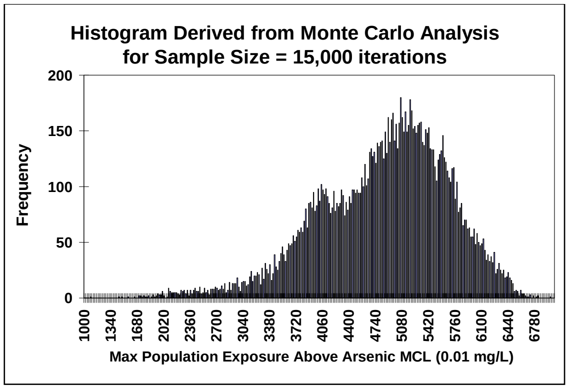
Fig. 4.15. Accounting for uncertainty in arsenic quantity used by intruder.

4.3.2. Uncertainty Propagation

An overview of uncertainty analysis guidelines for determining sample size convergence is provided by Morgan and Henrion [24]. Equation (4.4) was applied for determining the sample size for the Monte Carlo simulation based on uncertainty about the mean.

$$m > \left(\frac{2c\sigma}{w} \right)^2 \tag{4.4}$$

In Equation (4.4), m = sample size (number of iterations), c = critical value for 95% confidence interval (1.645), σ =standard deviation, and w =desired confidence interval width. For w =30, the necessary sample size was determined to be 13,204 for the 95% confidence interval. It was decided to perform 15,000 iterations. For 15,000 replications, the simulation resulted in the histogram and the corresponding probability density function shown in Fig. 4.16. The results prove to be quite significant in terms of arsenic exposure exceeding the MCL. Fig. 4.16(a) and Fig. 4.16(b) show two apparent modes. The first mode corresponds to 4000 people exposed above the MCL, with an approximate probability density function (PDF) value of 0.007. The second mode corresponds to 5000 people exposed above the MCL, with an approximate PDF value of 0.012. This should be enough to raise concerns for any water provider. Exposures of this magnitude include damage to human health, financial establishments, WDS components, fear, and loss of public confidence in water utilities.

a) 

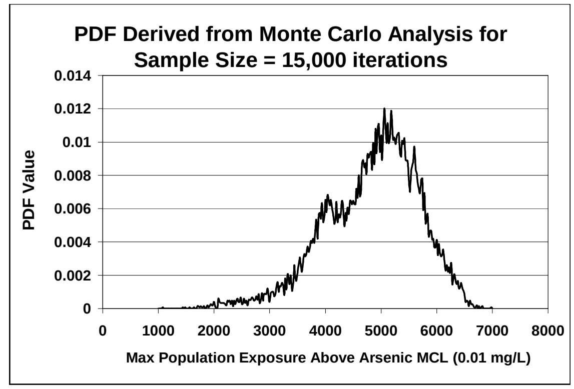
b) 

Fig. 4.16. Monte Carlo results for (a) arsenic exposure histogram and (b) probability density function.

Referring to Fig. 4.16 and recalling that Micropolis is only a 5,000 person city; the notion of 5,000 persons being exposed in only a portion of the city (those within the spread boundary) may seem questionable. Fig. 4.16 is based on exposure resulting from daily demand. Therefore, one person may become exposed to arsenic at home, then again at work. This person gets counted twice, because the intruder is essentially causing twice the harm. The next step was to further investigate the reasoning behind the bimodal phenomenon of Fig. 4.16 and to evaluate the variability within the Monte Carlo results from a time series perspective.

4.4. Phase IV – Further Evaluation of Maximum Contaminant Level Exposures

To help explain the bimodal characteristics of Fig. 4.16, a population density map was created using a GIS (Fig. 4.17). Also indicated on the map is the portion of

Micropolis that receives water that has passed through the storage tank. It was first hypothesized that the apartment complex was the reason for the bimodality, as the total population for the apartment complex is 640, with a total base demand of 663 L/min (175 gpm).

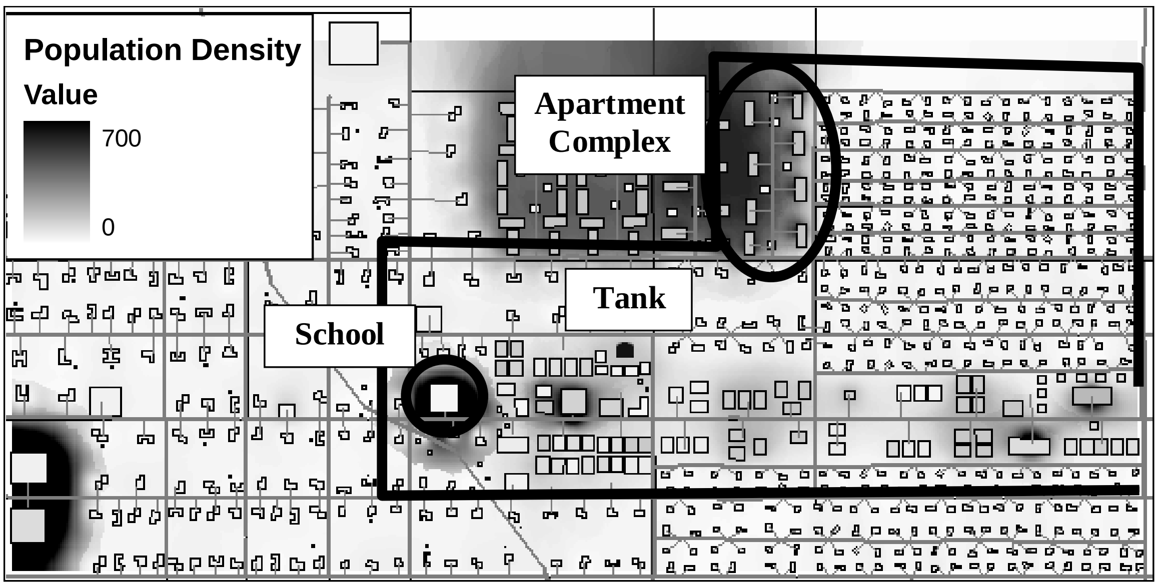


Fig. 4.17. Population density map.

To determine whether the apartment complex was indeed the cause, population values for the apartment complex were temporarily set to zero in the Monte Carlo analysis. This was done rather than assigning zero water demands for the reason that doing so would have altered flow directions, and thus contamination spread. The 15,000 iteration process was repeated. The result for this new scenario is shown as the broken curve in Fig. 4.18. The distribution remains bimodal, only it has shifted approximately 640 people to the left from the original distribution.

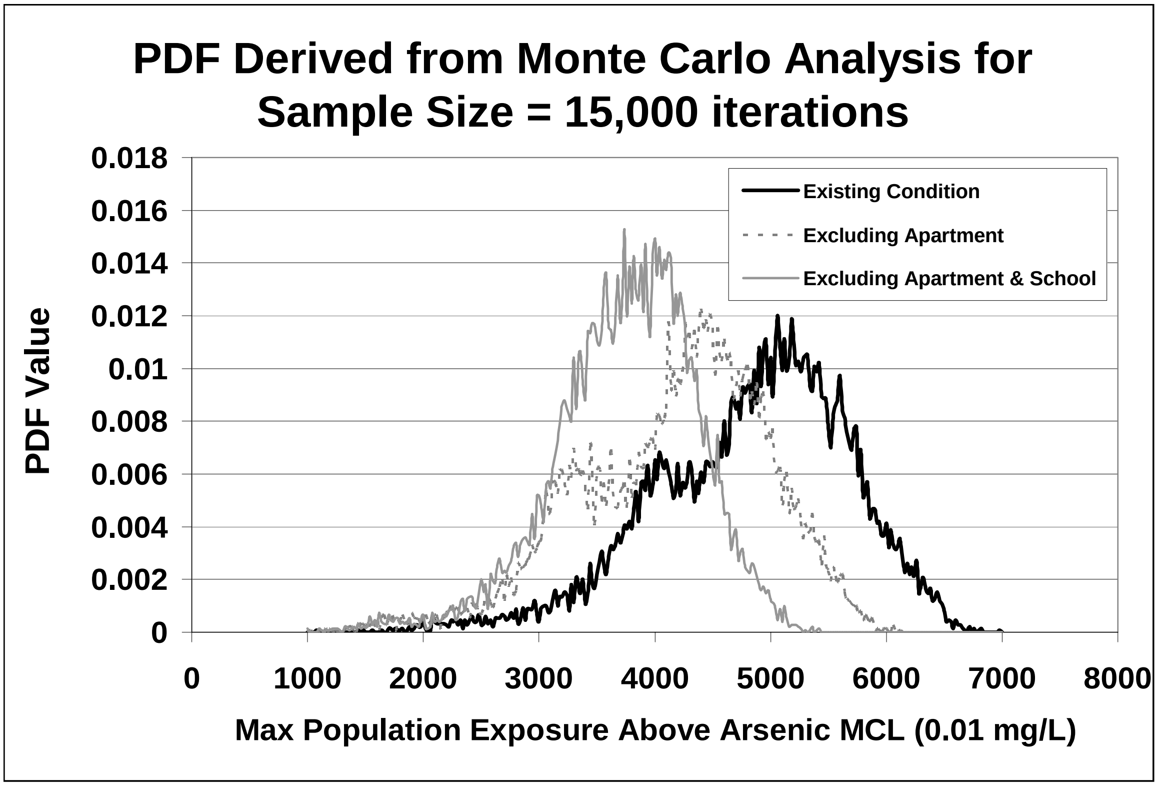


Fig. 4.18. PDF results for arsenic exposure investigation derived from Monte Carlo analysis.

Further investigation shows that the elementary school at the southwest corner of the spread area (Fig. 4.17) poses another possibility for the bimodal results. The school population accounts for 700 students, faculty, and staff with a base demand of 296 L/min (78 gpm). The 15,000 iteration process was repeated with the population values for the apartment complex and school temporarily removed from the analysis. The result is shown as the gray solid curve in Fig. 4.18. As this figure shows, the bimodality is no longer present. In fact, the resulting distribution lends itself quite well to a normal distribution. The two modes are thus seen to exist for replications with the school in session (right mode) and out of session (left mode). This observation demonstrates the effect that a concentration of users at a single location may have on contaminant exposure and how itinerant water usage at this location may lead to bifurcated system behavior and expectations of consequences.

To convey variability in population exposure through the 72 hour simulation period, a quartile graph derived from the Monte Carlo results is shown Fig. 4.19.

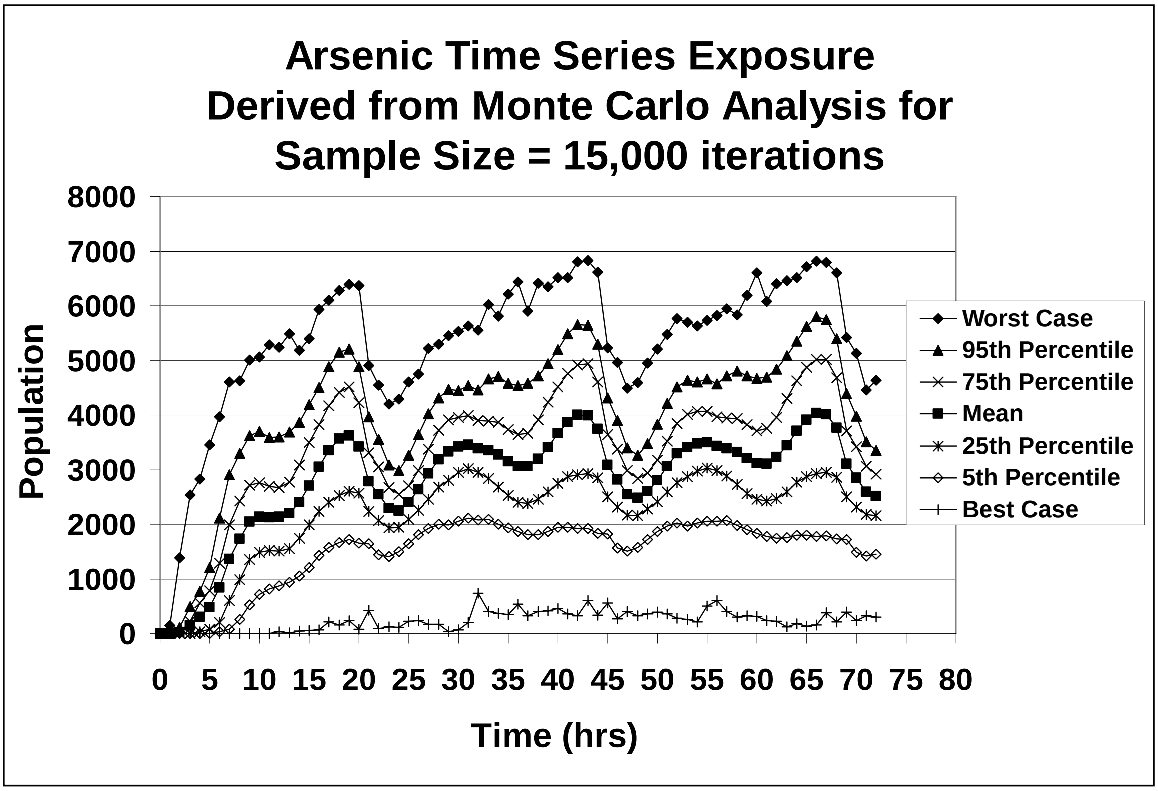


Fig. 4.19. Time series MCL exposures derived from Monte Carlo analysis.

The curve with square markers represents the mean over 15,000 data points, as do other curves for their respective quartiles. It can be gathered from Fig. 4.19 that reasonable uncertainties in model inputs produce high variability in exposure levels. It is also shown that exposure rises quickly during the initial stages of the contamination event. Understandably, exposure decreases when demand decreases, such as during nighttime. In the best case (least exposure) result, approximately 750 people are exposed above the MCL around the 32nd hour, which is about one-tenth the total possible. This level of exposure could conceivably incite significant public fear. The worst case results in approximately 7,000 people exposed, which is effectively the full population including the “double exposed, double counted” effect.

An important note learned from this additional evaluation is that when performing risk analysis, risk classification, and/or vulnerability assessments, it is necessary to understand how the water distribution system of interest is hydraulically idiosyncratic. Only by applying uncertainty propagation techniques and performing further investigations was useful knowledge about the hydraulic behavior and contamination spread gained. Phase V shows how this additional knowledge helps to refine mitigation strategies.

4.5. Phase V – Mitigation Strategies

Four mitigation strategies are presented in Fig. 4.20. They include topological modifications to the existing pipe network, valve installation, and an emergency purging system, and a combination strategy. The proposed strategies are based on the previously discussed exposure results. Their effectiveness is illustrated in Fig. 4.21 for a 72 hour time series compared to the base-case (no mitigation) scenario.

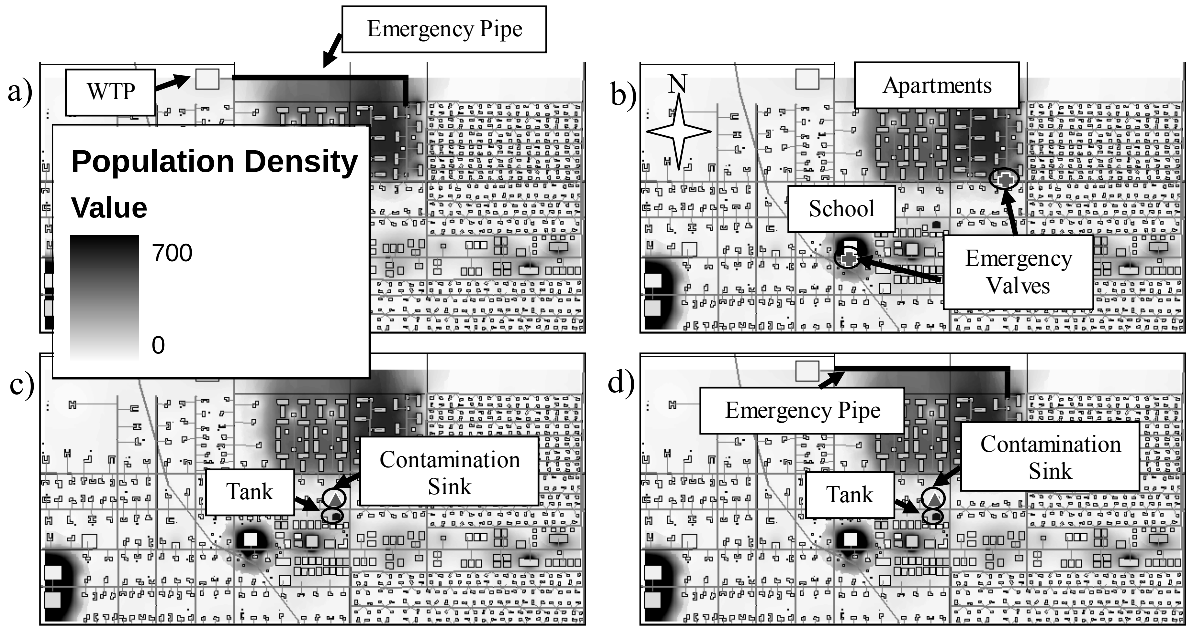


Fig. 4.20. Mitigation strategies: (a) emergency pipe installation, (b) emergency valve installation, (c) contamination sink, and (d) emergency pipe and contamination sink.

Mitigation Strategy 1 involves the addition of an emergency pipeline that connects the apartment complex water main directly to the water treatment plant. This is labeled and shown in Fig. 4.20(a) with a thick black line. This pipe would be a 518 m (1700-ft) long, 305 mm (12-in) diameter ductile iron water main to be used in the case of a contamination event. It was hypothesized that the provision of clean water from this pipe would offset exposure from those receiving contaminated water. The result for this mitigation strategy is presented as the curve with square markers in Fig. 4.21. This strategy does not prove to be very effective, as maximum exposure levels are similar to the base-case scenario. This is because added flow from the new line changes flow patterns to “push” the contaminant to a different group of users.

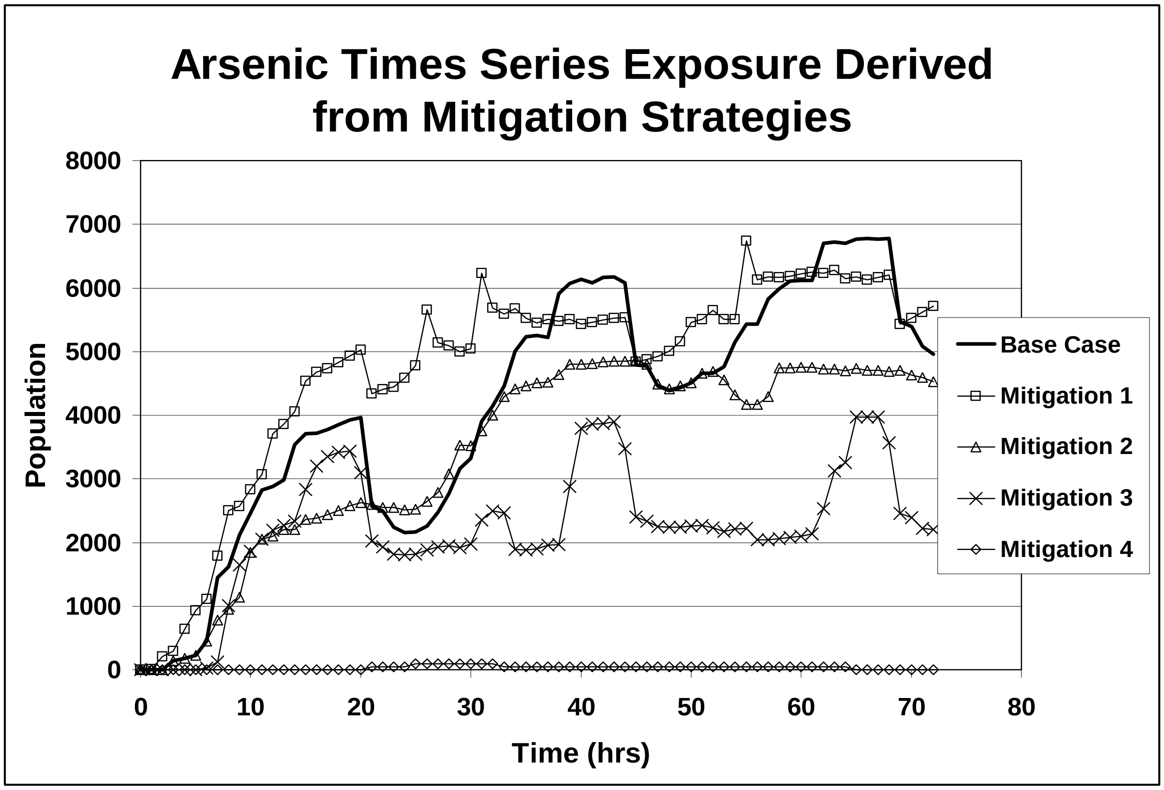


Fig. 4.21. Time series arsenic exposure for each mitigation strategy.

Mitigation Strategy 2 involves adding emergency valves to the demand nodes that are known to account for the majority of the population who depend on water supply from the tank, i.e., the apartment complex and school. The valve locations are labeled and shown in Fig. 4.20(b) as crosses. It was hypothesized that once contamination was detected near the tank by way of real-time water quality sensors, valves would be programmed to close, thereby prohibiting spread to these highly populated areas. The result for this mitigation strategy is presented as the curve with triangle markers in Fig. 4.21. This curve shows a slight improvement, but the amount of people exposed above the MCL remains high.

Mitigation Strategy 3 entails an emergency purging system which utilizes a contamination "sink" near the storage tank. This is labeled and shown as a triangle in Fig. 4.20(c). A contamination sink could represent an empty underground storage tank with high capacity for water storage, and located near the water supply tank. It was hypothesized that the sink would draw water with a constant demand of 1124 L/min (297 gpm). This is the highest demand that could be achieved while still maintaining fire flow pressures of 138 kPa (20 psi), as required throughout the city. Real-time sensor monitoring near the tank would activate the sink and drain most of the arsenic residual. The stored arsenic could then be treated before discharge. The result for this mitigation strategy is presented as the curve with cross markers in Fig. 4.21. This curve shows a significant improvement, but the amount of people exposed above the MCL remains high.

Because the third strategy was limited by the ability to maintain fire flow pressures, Mitigation Strategy 4 combines the first and third strategies to form a "hybrid" mitigation strategy. The emergency pipe installation and contamination sink are shown in Fig. 4.20(d). Because water supply is added to eastern Micropolis, the sink demand can be increased to a constant 1514 L/min (400 gpm), while maintaining fire flows. Again, real-time sensor monitoring near the tank would activate the sink for the draining of arsenic, while activating the emergency pipe for clean water supply and added pressure. The stored arsenic could then be treated before discharge. The result for this mitigation strategy is presented as the curve with diamond markers in Fig. 4.21. This curve shows few people exposed above the MCL, and those who are, experience exposure levels near the MCL.

As shown, the Mitigation Strategy 4 was proven to be the most effective for reducing arsenic exposure. This strategy relies upon a sophisticated control system actuated by real-time water quality sensors. At present, such sensors are under development for many potential contaminants and are not widely available. However, in anticipation of their deployment, optimization schemes are currently under development for sensor placement [25]. Work has also been performed in the identification of efficient threat management strategies through simulation and analysis of contamination events for water distribution systems [26]. It has also been suggested that an all hazard approach would aid in managing threats to critical infrastructures [27]. This includes infrastructure threats due to hurricanes, earthquakes, floods, fires, etc.

The contamination sink "footprint" is also ill-defined. The sink is purely hypothetical, to be seen mainly as a safeguard with unlimited capacity and high demand. However, the installation of safety valves and emergency pipelines can be considered reasonable for a small town like Micropolis.

A less costly alternative would be to hire trustworthy staff to monitor "out of the ordinary" radio calls, in the instance that isolation valves need to be closed at moment's notice. An emergency preparedness plan and communication with city residents would also educate the public on what to do during critical infrastructure failure. In the case of decision making, multiattribute utility theory could be of most importance. This would involve developing a utility function(s) that could account for both uncertainties and risks for malevolent WDS sabotage. The decision for which expected utility is maximized would be chosen.

5. IMPROVING THE EMERGENCY MANAGEMENT PROCESS FOR WATER SUPPLY CONTAMINATION EVENTS

This section develops the basis for improving existing methods for mitigating, preparing for, responding to, and recovering from WDS contamination events. Fig. 5.1 illustrates a generalized disaster life cycle for emergency management planning [28].

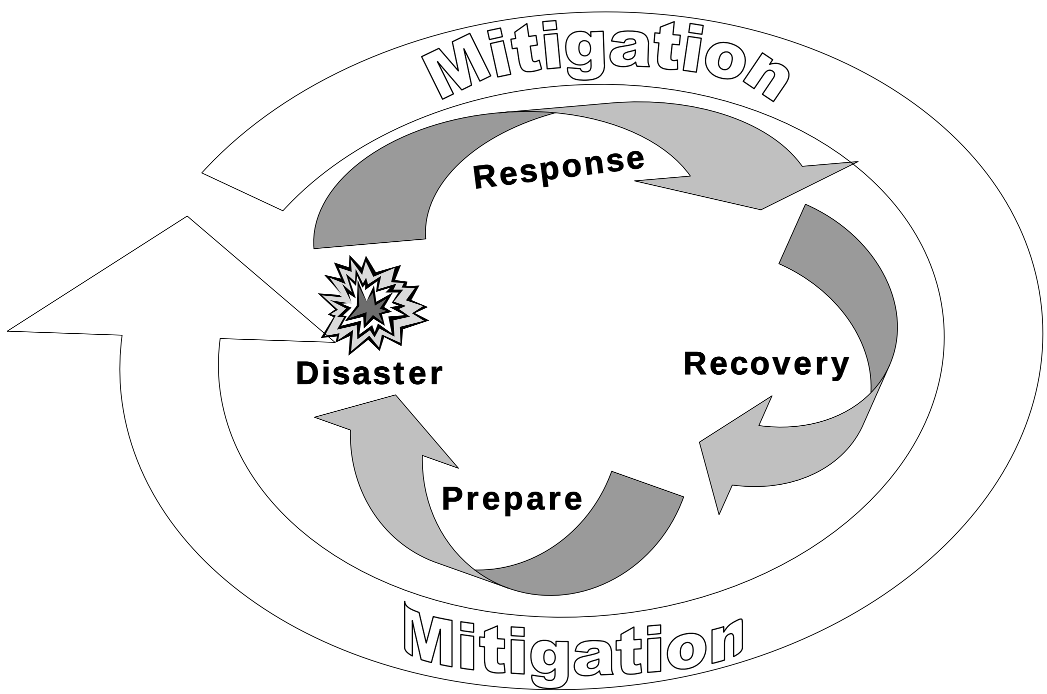


Fig. 5.1. Emergency management: the disaster life cycle [28].

Following some known disaster, a water utility is expected to be prepared to respond immediately through intelligence gathering, verification, and providing citizens with adequate information in a timely manner. This stage is followed by recovery efforts for restoring the WDS back to acceptable levels of operation by restoring water quality and rectifying any physical damages. These preparation measures should be in place before a disaster occurs. Following a recovery, emergency management procedures should be re-evaluated and updated to reflect unexpected events in the previous disaster, and to reflect changing external conditions. A water utility should also take note that the degrees of WDS vulnerability to contamination events are not constant. Rather, they change as the city's population and economy redistributes itself geographically [29]. Therefore, mitigation measures should not be held constant, but should also be continuously re-evaluated and updated as necessary. Each element within the disaster life cycle is discussed in further detail with recommendations for improving WDS security.

5.1. Mitigation

Before a water utility can commence mitigation on a WDS, a detailed vulnerability assessment should be conducted in order to identify what areas of the system need the most attention. It would make sense for the vulnerability assessor to one with experience and knowledge of the WDS. Table 5.1 shows a generalized process, suggested by AWWA [12], for conducting a vulnerability assessment for a water distribution system.

Table 5.1. The vulnerability assessment process [12].

Step	Activity
1	Identify major system components
2	Determine effects of probable disaster
3	Establish performance goals and acceptable levels of service
4	Identify critical components

Step 1 calls for water utilities to identify all major system components. For a water distribution system this includes: treatment facilities, pump stations, intake locations, storage tanks, control rooms, etc. Step 2 looks at the major system components from Step 1, and raises the question, “How would my system function during a contamination event and what might be the effects of such an event?” Step 3 establishes performance goals and acceptable levels of service. In regard to a contamination event, this means returning the water quality and pressures to acceptable levels of service. Finally, Step 4 narrows down the identified components from Step 1, and asks the question, “Which components are most likely to fail, become breached, or become a source point for contamination?” Step 2 is perhaps the most difficult step. It requires the assessor to predict what areas of the WDS would become exposed to tainted water in the event of a contamination attack. For many water utilities, especially small ones, predictions are as good as it gets. Unfortunately, WDSs are not intuitive systems. Given the high degree of safety and health at risk, it would be unwise to base mitigation programs on simple assumptions of contamination spread behavior. One solution is to adopt a scenario-based modeling approach. This approach is similar to that discussed in *Section 4.2., Phase II – Simulation of a Base-Case Contamination Event.* For example, following Step 4 of the vulnerability assessment process, the assessor is said to have identified the elevated storage tank as a prime target for a contamination attack. The vulnerability assessor wishes to know the probable behavior of contamination spread if the tank were to become breached. At this point, the assessor can refer to the results of *Phase II – Simulation of a Base-Case Contamination Event* such as that shown in Fig. 4.6. The assessor could then resume with the proposition and modeling of several effective mitigation strategies, such as those mentioned in *Section 4.5., Phase V – Mitigation Strategies.*

Recall that Mitigation Strategy 4 proved most effective. However, as this strategy entails, words like “real-time water quality sensors”, “1700 ft. pipe installations,” and “high demand storage tanks,” it would probably not prove to be as attractive to water utilities on limited budgets, therefore mitigation strategies should be chosen to be cost effective. Providing simple education to water utility personnel and residents about contamination awareness could be considered an effective mitigation measure. Adding WDS redundancy by adding alternate sources of water supply, such as treated water stored offsite could prove beneficial. The installation of updated locks, adequate lighting, multi-barrier fencing, and window security at control rooms could also reduce the likelihood of successful attack. Other adjustments include adding motion detectors, closed-circuit surveillance, and clearing shrubbery and brush around facilities that could impair surveillance monitoring.

Like viruses, intruders can become immune to existing mitigation measures. This can happen when an intruder's attack strategy or priority evolves in order to counter increased security measures. In addition, as the population and economy re-distributes themselves, demand stresses will be added to the water distribution system [29]. To meet these changes, mitigation measures require continuous re-evaluation and updating.

5.2. Preparedness

Before a contamination event occurs, a preparation policy should already be in place. Utility personnel and representatives from the community need to be comfortable with some type of drill (such as fire drills) or table-top exercises on a regular basis. Funding for preparation programs is available from the EPA through grants. This is especially attractive for small towns with limited budgets. In addition to drills, exercises, and funding, coordination with other agencies should also be a priority. Water utilities, fire departments, police departments, emergency medical services (EMS), and hospitals are only a few of the organizations that need to be capable of working together in an efficient manner during a water supply contamination attack. In addition to these emergency services, consortiums and non-governmental organizations (NGO) should also be included in the coordination "loop."

5.3. Response

If a contamination attack to a city's water distribution system were to occur, would that city be prepared to respond? This is the essential question for this thesis. According to the Federal Bioterrorism and Response Act of 2002, they should be. This act required all towns greater than 3,300 to conduct vulnerability assessments of their water system and prepare emergency response plans. However, EPA only requires these cities to submit certifications of compliance, and not the actual vulnerability assessments. This sort of process is susceptible to "cutting corners" on vulnerability assessments and hazard mitigation plans. At this point, it would be difficult to ascertain the true level of preparedness from the literature and from calling water utilities directly, nevertheless efforts are underway to find the best answers possible. As guidance to North American water utilities, AWWA [12] has adopted the generalized emergency response process shown in Table 5.2.

Table 5.2. The emergency response process [12].

Step	Activity
1	Detect
2	Analyze Severity
3	Isolate
4	Purge

Referring to Step 1, before it can respond, a water utility should be able to detect and verify that a contamination event has occurred. Detection capability includes, but is not limited to, water quality monitoring and the monitoring of health reports at hospitals. From the moment of contamination event initiation, to detection, to response, there exists a significant delay in time. This can have a significant impact on the amount of lives exposed to contaminated water. Efforts have been made to model this delay by Bristow and Brumbelow [9], as previously discussed in *Section 2.1., Vulnerability Assessments for Water Distribution Systems*.

Step 2 analyzes the severity of the incident following detection. A water distribution system is too large and complex to analyze at once, therefore, with the help of previous vulnerability assessments and hydraulic models, one can eliminate portions of the system not likely to experience contaminant exposure. Step 3 establishes the next priority by taking the necessary actions to isolate the contaminant from further spread. Field and modeling analysis would help determine which areas to isolate based on the contamination spread boundary. Step 4 involves purging the system of tainted water. This could require simple flushing from fire hydrants into storm sewers, or treating the water before releasing it back into the environment.

It is obvious that a successful emergency response involves clear communications. For example, citizens require rapid alert information for complying with warnings about their drinking water. It is almost shocking, given our current "information age," that utilities still struggle with significant time delays in detecting and responding to contamination incidents. Television, radio, email, text messaging, and sirens (TRETS) are all tools that exhibit great potential for providing maximum rapid information to citizens in the event of an intentional, accidental, or natural breach of a water distribution system. The concept with TRETS is that at any given time residents are likely to be watching television, listening to the radio, checking email, carrying a cellular phone, or outside capable of hearing a siren. Of these five tools, one to note is the technology for text messaging via cellular phones. Text messaging is still largely unused by emergency planners. Universities are just now beginning to utilize this resource as a result of the tragedy at Virginia Tech on April 16, 2007. Texas A&M University has initiated the Code Maroon text messaging system for relaying emergency information to students, faculty, and staff. Another tool of note is the use of sirens. If a siren is properly sounded over an effective range, citizens can translate this into action by tuning into the local news network on a television, radio, or by checking text messages and email for up-to-date information. Perry and Lindell [30] have noted, that when confronted with a disaster, citizens are capable of making wise decisions, should be expected to take action, and should be expected to comply with authority recommendations if they are provided with adequate information in a timely manner.

Another current technological disadvantage is the lack of availability of real-time water quality sensors. These sensors are currently under development. They should not only be real-time detection sensors, but comprehensive in terms of what they can detect. These sensors should be capable of detecting most contaminants, either chemical, biological, or radiological. Bridging the gap between real-time water quality detection and rapid information to citizens would drastically improve current emergency response plans.

5.4. Recovery

Recovery efforts should begin immediately, even if the contaminant is still in the WDS. It should begin with the notification of utility personnel, residents, hospitals, emergency services, and the media during and after the event. Recovery also includes the provision of immediate medical assistance to those in need. Field sampling should continue in affected areas until the water supply is proven safe, and any physical damages to the system as a result of the attack should be repaired as soon as possible.

6. CONCLUSIONS

6.1. Analytical Conclusions

An investigation was conducted on exposure sensitivities to stochastic inputs and on mitigation measures for contaminant exposure reduction. Findings show that reasonable uncertainties in model inputs produce high variability in exposure levels. It is also shown that exposure level distributions experience noticeable sensitivity to population clusters within the contaminant spread area, i.e., the school and apartment complex. The significance in uncertainty for exposure patterns demonstrates the need for developing more resources to effective mitigation.

As an additional consideration, all water distribution systems are hydraulically unique and behave differently. If these hydraulic details are not included in risk models, important insights will be missed. This can easily be forgotten when performing probabilistic risk analysis, vulnerability assessments, and multiattribute utility theory when assessing WDS contamination risk. If reasonable results are to be obtained, then the understanding of basic fluid mechanics is also important. Knowing what direction water flows and how much of it is used at any given time is vital for gaining reasonable estimates on contamination exposure. Only by applying uncertainty propagation techniques and performing investigations was useful knowledge on the hydraulic and contamination spread behavior gained.

As is well known, an important goal for modeling risk and uncertainty for critical infrastructures is to provide a tool for those needing to make important decisions concerning public welfare. But for many researchers, this modeling is rather difficult considering the sensitive nature of the data being used. Because real city data is kept confidential, the concept of contributing to a library of virtual cities is vital for the research community. Information can be shared and insights gained from comparative development. Micropolis is the first entry into such a library, which is freely available for others' use. Although Micropolis is a virtual city, the methodologies used and insights gained through its modeling process may be adapted for real cities.

6.2. Non-Analytical Conclusions

It is not necessarily safe to assume that because a particular water user is located near a water source, this same user receives water from that source, and should therefore be accounted for in mitigation planning for a contamination attack of that same water source. If this instinctive behavior is chosen in place of hydraulic and water quality modeling of an actual WDS, then selected mitigation strategies can pose a potential for making contamination spread and human exposures far worse. Mitigation selection based on instinctive behavior was the basis for developing Mitigation Strategy 1, and as the results showed, it did nothing to reduce contamination exposure. The advantage of scenario-based modeling lies not only in the understanding of contamination spread behavior, but in proposals for various mitigation strategies. If one strategy proves ineffective, the modeler has the freedom to choose and re-simulate another. Having an effective mitigation plan can have a ripple effect in the rest of the disaster life cycle by increasing the chances of successful preparedness, response, and recovery efforts.

In addition to vulnerability assessments required by the Bioterrorism Act, a water utility should supplement mitigation and response procedures with extended period simulation models for the actual water distribution systems. By adopting a contamination event scenario modeling approach, a water utility can gain a better understanding of how contamination spreads from a given point. Therefore, scenario modeling and disaster planning should go hand in hand. Planning for mitigation, preparedness, response, and recovery should not be made worse by excessive guessing. Simply put, WDSs are too complex for one to assume intuitive development of mitigation, preparedness, response, and recovery based on “one size fits all” assessments. Every city’s plan will be unique due to their topology, economy, demography, etc. Every city not only has different WDSs, but different styles of policy, utility organization structures, and priorities.

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APPENDIX A

MONTE CARLO SIMULATION RESULTS

Table A.1. Monte Carlo simulation results for number of persons exposed above arsenic MCL (0.01 mg/L).

MC Results, 15,000 iterations			MC Results, 15,000 iterations excluding apartment			MC Results, 15,000 iterations excluding apartment and school		
Population	Frequency	PDF Value	Population	Frequency	PDF Value	Population	Frequency	PDF Value
1000	0	0.00000	1000	0	0.00000	1000	2	0.00013
1020	0	0.00000	1020	1	0.00007	1020	0	0.00000
1040	0	0.00000	1040	0	0.00000	1040	0	0.00000
1060	0	0.00000	1060	0	0.00000	1060	0	0.00000
1080	1	0.00007	1080	0	0.00000	1080	0	0.00000
1100	0	0.00000	1100	0	0.00000	1100	2	0.00013
1120	0	0.00000	1120	1	0.00007	1120	1	0.00007
1140	0	0.00000	1140	0	0.00000	1140	0	0.00000
1160	0	0.00000	1160	2	0.00013	1160	1	0.00007
1180	0	0.00000	1180	0	0.00000	1180	1	0.00007
1200	0	0.00000	1200	2	0.00013	1200	1	0.00007
1220	0	0.00000	1220	0	0.00000	1220	2	0.00013
1240	0	0.00000	1240	1	0.00007	1240	2	0.00013
1260	0	0.00000	1260	0	0.00000	1260	2	0.00013
1280	0	0.00000	1280	0	0.00000	1280	1	0.00007
1300	0	0.00000	1300	0	0.00000	1300	0	0.00000
1320	0	0.00000	1320	1	0.00007	1320	3	0.00020
1340	0	0.00000	1340	2	0.00013	1340	3	0.00020
1360	0	0.00000	1360	3	0.00020	1360	1	0.00007
1380	0	0.00000	1380	3	0.00020	1380	2	0.00013
1400	0	0.00000	1400	0	0.00000	1400	3	0.00020
1420	0	0.00000	1420	0	0.00000	1420	2	0.00013
1440	1	0.00007	1440	5	0.00033	1440	5	0.00033
1460	0	0.00000	1460	4	0.00027	1460	2	0.00013
1480	1	0.00007	1480	5	0.00033	1480	3	0.00020
1500	0	0.00000	1500	2	0.00013	1500	3	0.00020
1520	0	0.00000	1520	6	0.00040	1520	3	0.00020
1540	0	0.00000	1540	3	0.00020	1540	9	0.00060
1560	1	0.00007	1560	6	0.00040	1560	4	0.00027
1580	0	0.00000	1580	3	0.00020	1580	7	0.00047
1600	0	0.00000	1600	7	0.00047	1600	3	0.00020
1620	0	0.00000	1620	1	0.00007	1620	11	0.00073
1640	1	0.00007	1640	8	0.00053	1640	6	0.00040
1660	0	0.00000	1660	10	0.00067	1660	5	0.00033
1680	0	0.00000	1680	4	0.00027	1680	5	0.00033
1700	2	0.00013	1700	8	0.00053	1700	10	0.00067
1720	2	0.00013	1720	7	0.00047	1720	7	0.00047
1740	1	0.00007	1740	9	0.00060	1740	6	0.00040
1760	2	0.00013	1760	1	0.00007	1760	8	0.00053
1780	1	0.00007	1780	7	0.00047	1780	8	0.00053
1800	1	0.00007	1800	6	0.00040	1800	5	0.00033
1820	2	0.00013	1820	10	0.00067	1820	6	0.00040
1840	0	0.00000	1840	6	0.00040	1840	5	0.00033

Table A.1. (Continued)

MC Results, 15,000 iterations			MC Results, 15,000 iterations excluding apartment			MC Results, 15,000 iterations excluding apartment and school		
Population	Frequency	PDF Value	Population	Frequency	PDF Value	Population	Frequency	PDF Value
1860	1	0.00007	1860	5	0.00033	1860	6	0.00040
1880	3	0.00020	1880	5	0.00033	1880	8	0.00053
1900	1	0.00007	1900	11	0.00073	1900	3	0.00020
1920	2	0.00013	1920	8	0.00053	1920	5	0.00033
1940	4	0.00027	1940	8	0.00053	1940	4	0.00027
1960	3	0.00020	1960	7	0.00047	1960	3	0.00020
1980	3	0.00020	1980	6	0.00040	1980	7	0.00047
2000	6	0.00040	2000	7	0.00047	2000	10	0.00067
2020	2	0.00013	2020	10	0.00067	2020	2	0.00013
2040	0	0.00000	2040	6	0.00040	2040	2	0.00013
2060	1	0.00007	2060	4	0.00027	2060	3	0.00020
2080	9	0.00060	2080	5	0.00033	2080	11	0.00073
2100	6	0.00040	2100	10	0.00067	2100	6	0.00040
2120	5	0.00033	2120	9	0.00060	2120	7	0.00047
2140	5	0.00033	2140	2	0.00013	2140	6	0.00040
2160	5	0.00033	2160	7	0.00047	2160	8	0.00053
2180	5	0.00033	2180	8	0.00053	2180	10	0.00067
2200	4	0.00027	2200	11	0.00073	2200	9	0.00060
2220	3	0.00020	2220	12	0.00080	2220	12	0.00080
2240	7	0.00047	2240	15	0.00100	2240	13	0.00087
2260	6	0.00040	2260	11	0.00073	2260	15	0.00100
2280	7	0.00047	2280	14	0.00093	2280	7	0.00047
2300	4	0.00027	2300	13	0.00087	2300	9	0.00060
2320	7	0.00047	2320	10	0.00067	2320	17	0.00113
2340	2	0.00013	2340	11	0.00073	2340	19	0.00127
2360	7	0.00047	2360	12	0.00080	2360	12	0.00080
2380	4	0.00027	2380	14	0.00093	2380	19	0.00127
2400	7	0.00047	2400	8	0.00053	2400	20	0.00133
2420	9	0.00060	2420	17	0.00113	2420	20	0.00133
2440	6	0.00040	2440	14	0.00093	2440	16	0.00107
2460	6	0.00040	2460	16	0.00107	2460	14	0.00093
2480	10	0.00067	2480	11	0.00073	2480	22	0.00147
2500	4	0.00027	2500	10	0.00067	2500	30	0.00200
2520	5	0.00033	2520	15	0.00100	2520	23	0.00153
2540	9	0.00060	2540	21	0.00140	2540	27	0.00180
2560	5	0.00033	2560	20	0.00133	2560	13	0.00087
2580	7	0.00047	2580	17	0.00113	2580	33	0.00220
2600	3	0.00020	2600	14	0.00093	2600	29	0.00193
2620	8	0.00053	2620	19	0.00127	2620	28	0.00187
2640	8	0.00053	2640	22	0.00147	2640	38	0.00253
2660	8	0.00053	2660	26	0.00173	2660	42	0.00280
2680	10	0.00067	2680	30	0.00200	2680	34	0.00227
2700	9	0.00060	2700	18	0.00120	2700	35	0.00233

Table A.1. (Continued)

MC Results, 15,000 iterations			MC Results, 15,000 iterations excluding apartment			MC Results, 15,000 iterations excluding apartment and school		
Population	Frequency	PDF Value	Population	Frequency	PDF Value	Population	Frequency	PDF Value
2720	7	0.00047	2720	33	0.00220	2720	34	0.00227
2740	8	0.00053	2740	26	0.00173	2740	38	0.00253
2760	11	0.00073	2760	31	0.00207	2760	41	0.00273
2780	8	0.00053	2780	21	0.00140	2780	49	0.00327
2800	13	0.00087	2800	24	0.00160	2800	51	0.00340
2820	5	0.00033	2820	39	0.00260	2820	43	0.00287
2840	7	0.00047	2840	36	0.00240	2840	50	0.00333
2860	14	0.00093	2860	37	0.00247	2860	53	0.00353
2880	7	0.00047	2880	38	0.00253	2880	54	0.00360
2900	13	0.00087	2900	41	0.00273	2900	52	0.00347
2920	13	0.00087	2920	43	0.00287	2920	50	0.00333
2940	13	0.00087	2940	50	0.00333	2940	67	0.00447
2960	18	0.00120	2960	45	0.00300	2960	53	0.00353
2980	10	0.00067	2980	48	0.00320	2980	78	0.00520
3000	6	0.00040	3000	51	0.00340	3000	78	0.00520
3020	14	0.00093	3020	53	0.00353	3020	72	0.00480
3040	15	0.00100	3040	67	0.00447	3040	63	0.00420
3060	15	0.00100	3060	80	0.00533	3060	84	0.00560
3080	11	0.00073	3080	67	0.00447	3080	86	0.00573
3100	12	0.00080	3100	68	0.00453	3100	82	0.00547
3120	19	0.00127	3120	86	0.00573	3120	94	0.00627
3140	24	0.00160	3140	85	0.00567	3140	101	0.00673
3160	15	0.00100	3160	79	0.00527	3160	109	0.00727
3180	20	0.00133	3180	92	0.00613	3180	118	0.00787
3200	20	0.00133	3200	92	0.00613	3200	129	0.00860
3220	23	0.00153	3220	85	0.00567	3220	132	0.00880
3240	21	0.00140	3240	78	0.00520	3240	127	0.00847
3260	12	0.00080	3260	95	0.00633	3260	123	0.00820
3280	27	0.00180	3280	88	0.00587	3280	120	0.00800
3300	17	0.00113	3300	105	0.00700	3300	156	0.01040
3320	31	0.00207	3320	92	0.00613	3320	127	0.00847
3340	26	0.00173	3340	93	0.00620	3340	158	0.01053
3360	22	0.00147	3360	89	0.00593	3360	160	0.01067
3380	30	0.00200	3380	92	0.00613	3380	143	0.00953
3400	16	0.00107	3400	83	0.00553	3400	133	0.00887
3420	22	0.00147	3420	70	0.00467	3420	171	0.01140
3440	39	0.00260	3440	107	0.00713	3440	170	0.01133
3460	28	0.00187	3460	91	0.00607	3460	176	0.01173
3480	25	0.00167	3480	61	0.00407	3480	175	0.01167
3500	33	0.00220	3500	92	0.00613	3500	166	0.01107
3520	40	0.00267	3520	94	0.00627	3520	163	0.01087
3540	46	0.00307	3540	74	0.00493	3540	172	0.01147
3560	39	0.00260	3560	85	0.00567	3560	194	0.01293

Table A.1. (Continued)

MC Results, 15,000 iterations			MC Results, 15,000 iterations excluding apartment			MC Results, 15,000 iterations excluding apartment and school		
Population	Frequency	PDF Value	Population	Frequency	PDF Value	Population	Frequency	PDF Value
3580	33	0.00220	3580	72	0.00480	3580	204	0.01360
3600	43	0.00287	3600	84	0.00560	3600	173	0.01153
3620	49	0.00327	3620	104	0.00693	3620	172	0.01147
3640	47	0.00313	3640	80	0.00533	3640	164	0.01093
3660	49	0.00327	3660	71	0.00473	3660	176	0.01173
3680	56	0.00373	3680	71	0.00473	3680	203	0.01353
3700	51	0.00340	3700	80	0.00533	3700	176	0.01173
3720	55	0.00367	3720	82	0.00547	3720	196	0.01307
3740	61	0.00407	3740	85	0.00567	3740	229	0.01527
3760	59	0.00393	3760	71	0.00473	3760	180	0.01200
3780	63	0.00420	3780	98	0.00653	3780	208	0.01387
3800	59	0.00393	3800	77	0.00513	3800	187	0.01247
3820	69	0.00460	3820	85	0.00567	3820	214	0.01427
3840	80	0.00533	3840	84	0.00560	3840	193	0.01287
3860	63	0.00420	3860	102	0.00680	3860	189	0.01260
3880	85	0.00567	3880	94	0.00627	3880	209	0.01393
3900	86	0.00573	3900	93	0.00620	3900	182	0.01213
3920	81	0.00540	3920	107	0.00713	3920	221	0.01473
3940	95	0.00633	3940	105	0.00700	3940	185	0.01233
3960	78	0.00520	3960	109	0.00727	3960	169	0.01127
3980	83	0.00553	3980	110	0.00733	3980	215	0.01433
4000	98	0.00653	4000	104	0.00693	4000	224	0.01493
4020	87	0.00580	4020	124	0.00827	4020	203	0.01353
4040	102	0.00680	4040	123	0.00820	4040	219	0.01460
4060	97	0.00647	4060	118	0.00787	4060	201	0.01340
4080	93	0.00620	4080	122	0.00813	4080	212	0.01413
4100	98	0.00653	4100	127	0.00847	4100	206	0.01373
4120	91	0.00607	4120	177	0.01180	4120	216	0.01440
4140	85	0.00567	4140	138	0.00920	4140	213	0.01420
4160	76	0.00507	4160	149	0.00993	4160	176	0.01173
4180	81	0.00540	4180	134	0.00893	4180	192	0.01280
4200	96	0.00640	4200	144	0.00960	4200	180	0.01200
4220	78	0.00520	4220	141	0.00940	4220	193	0.01287
4240	85	0.00567	4240	148	0.00987	4240	184	0.01227
4260	82	0.00547	4260	175	0.01167	4260	174	0.01160
4280	85	0.00567	4280	168	0.01120	4280	148	0.00987
4300	97	0.00647	4300	170	0.01133	4300	155	0.01033
4320	92	0.00613	4320	161	0.01073	4320	156	0.01040
4340	74	0.00493	4340	172	0.01147	4340	143	0.00953
4360	86	0.00573	4360	156	0.01040	4360	149	0.00993
4380	79	0.00527	4380	171	0.01140	4380	127	0.00847
4400	91	0.00607	4400	184	0.01227	4400	122	0.00813
4420	85	0.00567	4420	173	0.01153	4420	106	0.00707

Table A.1. (Continued)

MC Results, 15,000 iterations			MC Results, 15,000 iterations excluding apartment			MC Results, 15,000 iterations excluding apartment and school		
Population	Frequency	PDF Value	Population	Frequency	PDF Value	Population	Frequency	PDF Value
4440	97	0.00647	4440	178	0.01187	4440	123	0.00820
4460	97	0.00647	4460	171	0.01140	4460	112	0.00747
4480	94	0.00627	4480	181	0.01207	4480	101	0.00673
4500	97	0.00647	4500	173	0.01153	4500	93	0.00620
4520	94	0.00627	4520	146	0.00973	4520	84	0.00560
4540	94	0.00627	4540	173	0.01153	4540	112	0.00747
4560	108	0.00720	4560	159	0.01060	4560	85	0.00567
4580	100	0.00667	4580	154	0.01027	4580	86	0.00573
4600	120	0.00800	4600	167	0.01113	4600	67	0.00447
4620	101	0.00673	4620	155	0.01033	4620	68	0.00453
4640	107	0.00713	4640	159	0.01060	4640	67	0.00447
4660	131	0.00873	4660	154	0.01027	4660	47	0.00313
4680	134	0.00893	4680	133	0.00887	4680	54	0.00360
4700	127	0.00847	4700	140	0.00933	4700	58	0.00387
4720	131	0.00873	4720	149	0.00993	4720	41	0.00273
4740	121	0.00807	4740	134	0.00893	4740	45	0.00300
4760	139	0.00927	4760	144	0.00960	4760	47	0.00313
4780	136	0.00907	4780	149	0.00993	4780	37	0.00247
4800	140	0.00933	4800	152	0.01013	4800	35	0.00233
4820	141	0.00940	4820	133	0.00887	4820	34	0.00227
4840	125	0.00833	4840	137	0.00913	4840	39	0.00260
4860	149	0.00993	4860	129	0.00860	4860	37	0.00247
4880	130	0.00867	4880	142	0.00947	4880	32	0.00213
4900	162	0.01080	4900	122	0.00813	4900	27	0.00180
4920	140	0.00933	4920	133	0.00887	4920	24	0.00160
4940	160	0.01067	4940	137	0.00913	4940	26	0.00173
4960	166	0.01107	4960	110	0.00733	4960	22	0.00147
4980	141	0.00940	4980	114	0.00760	4980	24	0.00160
5000	156	0.01040	5000	110	0.00733	5000	18	0.00120
5020	134	0.00893	5020	116	0.00773	5020	17	0.00113
5040	157	0.01047	5040	91	0.00607	5040	15	0.00100
5060	180	0.01200	5060	91	0.00607	5060	7	0.00047
5080	162	0.01080	5080	94	0.00627	5080	13	0.00087
5100	149	0.00993	5100	72	0.00480	5100	6	0.00040
5120	167	0.01113	5120	86	0.00573	5120	15	0.00100
5140	149	0.00993	5140	91	0.00607	5140	8	0.00053
5160	155	0.01033	5160	67	0.00447	5160	3	0.00020
5180	178	0.01187	5180	82	0.00547	5180	4	0.00027
5200	168	0.01120	5200	70	0.00467	5200	4	0.00027
5220	152	0.01013	5220	71	0.00473	5220	4	0.00027
5240	154	0.01027	5240	76	0.00507	5240	3	0.00020
5260	148	0.00987	5260	63	0.00420	5260	2	0.00013
5280	155	0.01033	5280	53	0.00353	5280	0	0.00000

Table A.1. (Continued)

MC Results, 15,000 iterations			MC Results, 15,000 iterations excluding apartment			MC Results, 15,000 iterations excluding apartment and school		
Population	Frequency	PDF Value	Population	Frequency	PDF Value	Population	Frequency	PDF Value
5300	157	0.01047	5300	62	0.00413	5300	1	0.00007
5320	158	0.01053	5320	57	0.00380	5320	0	0.00000
5340	140	0.00933	5340	57	0.00380	5340	1	0.00007
5360	137	0.00913	5360	68	0.00453	5360	3	0.00020
5380	151	0.01007	5380	54	0.00360	5380	0	0.00000
5400	148	0.00987	5400	51	0.00340	5400	1	0.00007
5420	153	0.01020	5420	52	0.00347	5420	2	0.00013
5440	134	0.00893	5440	38	0.00253	5440	0	0.00000
5460	133	0.00887	5460	55	0.00367	5460	0	0.00000
5480	133	0.00887	5480	38	0.00253	5480	0	0.00000
5500	118	0.00787	5500	35	0.00233	5500	0	0.00000
5520	105	0.00700	5520	29	0.00193	5520	0	0.00000
5540	124	0.00827	5540	37	0.00247	5540	0	0.00000
5560	129	0.00860	5560	32	0.00213	5560	0	0.00000
5580	132	0.00880	5580	28	0.00187	5580	0	0.00000
5600	146	0.00973	5600	32	0.00213	5600	0	0.00000
5620	126	0.00840	5620	33	0.00220	5620	0	0.00000
5640	122	0.00813	5640	22	0.00147	5640	0	0.00000
5660	114	0.00760	5660	19	0.00127	5660	0	0.00000
5680	108	0.00720	5680	18	0.00120	5680	0	0.00000
5700	104	0.00693	5700	16	0.00107	5700	0	0.00000
5720	116	0.00773	5720	15	0.00100	5720	0	0.00000
5740	117	0.00780	5740	15	0.00100	5740	0	0.00000
5760	89	0.00593	5760	11	0.00073	5760	0	0.00000
5780	104	0.00693	5780	12	0.00080	5780	0	0.00000
5800	77	0.00513	5800	7	0.00047	5800	0	0.00000
5820	81	0.00540	5820	10	0.00067	5820	0	0.00000
5840	85	0.00567	5840	8	0.00053	5840	0	0.00000
5860	65	0.00433	5860	6	0.00040	5860	0	0.00000
5880	70	0.00467	5880	8	0.00053	5880	0	0.00000
5900	70	0.00467	5900	0	0.00000	5900	0	0.00000
5920	62	0.00413	5920	2	0.00013	5920	0	0.00000
5940	63	0.00420	5940	1	0.00007	5940	0	0.00000
5960	55	0.00367	5960	0	0.00000	5960	0	0.00000
5980	55	0.00367	5980	2	0.00013	5980	0	0.00000
6000	62	0.00413	6000	2	0.00013	6000	0	0.00000
6020	48	0.00320	6020	0	0.00000	6020	0	0.00000
6040	58	0.00387	6040	0	0.00000	6040	0	0.00000
6060	50	0.00333	6060	4	0.00027	6060	0	0.00000
6080	47	0.00313	6080	0	0.00000	6080	0	0.00000
6100	49	0.00327	6100	0	0.00000	6100	0	0.00000
6120	53	0.00353	6120	1	0.00007	6120	0	0.00000
6140	43	0.00287	6140	0	0.00000	6140	0	0.00000

Table A.1. (Continued)

MC Results, 15,000 iterations			MC Results, 15,000 iterations excluding apartment			MC Results, 15,000 iterations excluding apartment and school		
Population	Frequency	PDF Value	Population	Frequency	PDF Value	Population	Frequency	PDF Value
6160	34	0.00227	6160	0	0.00000	6160	0	0.00000
6180	39	0.00260	6180	0	0.00000	6180	0	0.00000
6200	33	0.00220	6200	0	0.00000	6200	0	0.00000
6220	37	0.00247	6220	0	0.00000	6220	0	0.00000
6240	32	0.00213	6240	0	0.00000	6240	0	0.00000
6260	41	0.00273	6260	0	0.00000	6260	0	0.00000
6280	22	0.00147	6280	0	0.00000	6280	0	0.00000
6300	26	0.00173	6300	0	0.00000	6300	0	0.00000
6320	31	0.00207	6320	0	0.00000	6320	0	0.00000
6340	25	0.00167	6340	0	0.00000	6340	0	0.00000
6360	22	0.00147	6360	0	0.00000	6360	0	0.00000
6380	25	0.00167	6380	0	0.00000	6380	0	0.00000
6400	18	0.00120	6400	0	0.00000	6400	0	0.00000
6420	19	0.00127	6420	0	0.00000	6420	0	0.00000
6440	23	0.00153	6440	0	0.00000	6440	0	0.00000
6460	18	0.00120	6460	0	0.00000	6460	0	0.00000
6480	16	0.00107	6480	0	0.00000	6480	0	0.00000
6500	13	0.00087	6500	0	0.00000	6500	0	0.00000
6520	6	0.00040	6520	0	0.00000	6520	0	0.00000
6540	7	0.00047	6540	0	0.00000	6540	0	0.00000
6560	6	0.00040	6560	0	0.00000	6560	0	0.00000
6580	2	0.00013	6580	0	0.00000	6580	0	0.00000
6600	7	0.00047	6600	0	0.00000	6600	0	0.00000
6620	4	0.00027	6620	0	0.00000	6620	0	0.00000
6640	4	0.00027	6640	0	0.00000	6640	0	0.00000
6660	2	0.00013	6660	0	0.00000	6660	0	0.00000
6680	1	0.00007	6680	0	0.00000	6680	0	0.00000
6700	1	0.00007	6700	0	0.00000	6700	0	0.00000
6720	3	0.00020	6720	0	0.00000	6720	0	0.00000
6740	0	0.00000	6740	0	0.00000	6740	0	0.00000
6760	2	0.00013	6760	0	0.00000	6760	0	0.00000
6780	0	0.00000	6780	0	0.00000	6780	0	0.00000
6800	1	0.00007	6800	0	0.00000	6800	0	0.00000
6820	2	0.00013	6820	0	0.00000	6820	0	0.00000
6840	0	0.00000	6840	0	0.00000	6840	0	0.00000
6860	0	0.00000	6860	0	0.00000	6860	0	0.00000
6880	0	0.00000	6880	0	0.00000	6880	0	0.00000
6900	0	0.00000	6900	0	0.00000	6900	0	0.00000
6920	0	0.00000	6920	0	0.00000	6920	0	0.00000
6940	0	0.00000	6940	0	0.00000	6940	0	0.00000
6960	0	0.00000	6960	0	0.00000	6960	0	0.00000
6980	1	0.00007	6980	0	0.00000	6980	0	0.00000
7000	0	0.00000	7000	0	0.00000	7000	0	0.00000

Table A.2. Monte Carlo simulation results expressed as a time series quartile chart for number of persons exposed above arsenic MCL (0.01 mg/L).

Time (hrs)	Worst Case	95th Percentile	75th Percentile	Mean Percentile	25th Percentile	5th Percentile	Best Case
0	0	0	0	0	0	0	0
1	140	0	0	2	0	0	0
2	1384	107	2	25	0	0	0
3	2536	491	219	140	0	0	0
4	2822	772	556	305	34	0	0
5	3454	1207	787	484	83	0	0
6	3972	2112	1286	839	197	30	0
7	4601	2907	1994	1361	607	77	0
8	4623	3292	2424	1732	982	252	0
9	5008	3623	2718	2043	1351	524	0
10	5059	3693	2762	2132	1485	718	0
11	5284	3590	2696	2128	1515	812	3
12	5239	3602	2667	2131	1510	872	30
13	5484	3691	2770	2200	1556	941	13
14	5179	3866	3080	2405	1740	1047	49
15	5400	4195	3492	2702	1985	1208	58
16	5936	4508	3817	3056	2238	1429	72
17	6096	4888	4171	3349	2408	1579	209
18	6277	5151	4417	3565	2524	1667	153
19	6396	5207	4513	3617	2604	1721	238
20	6371	4886	4223	3414	2565	1654	80
21	4910	3962	3308	2783	2240	1648	422
22	4543	3555	3048	2544	2069	1436	93
23	4203	3089	2666	2291	1934	1410	121
24	4291	2982	2550	2248	1945	1497	111
25	4608	3258	2700	2402	2086	1648	222
26	4750	3637	2981	2638	2260	1810	236
27	5221	4022	3378	2926	2458	1927	173
28	5300	4317	3722	3190	2685	1997	172
29	5449	4467	3908	3334	2807	1986	36
30	5530	4450	3960	3417	2949	2056	63
31	5634	4537	3984	3448	3012	2107	200
32	5553	4460	3903	3387	2951	2080	739
33	6026	4664	3886	3357	2843	2089	397
34	5809	4704	3869	3277	2685	2000	368
35	6208	4585	3737	3151	2520	1931	348
36	6433	4540	3639	3058	2405	1862	535
37	5901	4584	3669	3057	2376	1810	323
38	6410	4719	3911	3192	2455	1807	398
39	6345	4940	4232	3408	2596	1861	413
40	6514	5198	4512	3668	2750	1940	455

Table A.2. (Continued)

Time (hrs)	Worst Case	95th Percentile	75th Percentile	Mean Percentile	25th Percentile	5th Percentile	Best Case
41	6517	5482	4756	3869	2868	1943	361
42	6799	5656	4915	3995	2907	1919	321
43	6823	5643	4935	3987	2929	1925	598
44	6619	5299	4599	3740	2850	1829	338
45	5229	4312	3648	3083	2505	1817	556
46	4965	3904	3369	2820	2317	1563	271
47	4491	3401	2978	2550	2172	1505	397
48	4596	3268	2833	2484	2162	1573	321
49	4955	3476	2939	2605	2282	1722	357
50	5203	3828	3170	2804	2418	1868	394
51	5477	4213	3516	3056	2589	1967	359
52	5762	4509	3845	3294	2764	2021	278
53	5700	4632	4012	3411	2868	1963	262
54	5636	4608	4069	3480	2976	2024	216
55	5733	4659	4072	3500	3031	2057	501
56	5816	4569	3962	3434	2981	2058	603
57	5945	4720	3945	3386	2878	2062	400
58	5827	4803	3930	3317	2724	1979	304
59	6192	4714	3819	3202	2564	1895	326
60	6606	4671	3708	3114	2453	1829	316
61	6080	4695	3751	3106	2423	1781	230
62	6406	4840	3956	3227	2471	1746	229
63	6457	5086	4303	3444	2592	1758	126
64	6518	5349	4622	3710	2774	1802	182
65	6714	5625	4875	3914	2877	1800	132
66	6811	5797	5014	4030	2933	1775	152
67	6796	5748	5014	4012	2949	1792	383
68	6605	5398	4681	3769	2861	1727	207
69	5421	4391	3712	3111	2507	1720	386
70	5123	3981	3424	2849	2316	1488	233
71	4460	3509	3065	2590	2180	1420	324
72	4640	3352	2919	2514	2162	1458	305

APPENDIX B

PROGRAM CODE

Sub Procedures

```
Option Explicit


Sub Simulate_Input_File()

Dim InputFile As String, ReportFile As String, BinaryFile As String, _
        id As String * 15, NodeID As String
Dim TermID As String, patid As String * 15
Dim t As Long, tstep As Long, tleft As Long, NumNodes As Long, i As Long, _
        j As Long, TermNodes As Long, m As Long
Dim Hydrants As Long, NumPipes As Long, Mains As Long, Svconn As Long, _
        NumIt As Long, index As Long
Dim ContamInit As Long, NextTimePer As Long
Dim BDemand As Single, p As Single, d As Single, c As Single, _
        ProgCounter As Single, InTankLevel As Single
Dim InitQualLevel As Single, NewTankLevel As Single, NewQualLevel As Single, _
        mean As Single, adjmultiplier As Single
Dim ElemDemand As Single, MidDemand As Single, HSDemand As Single, _
        u As Single, patindex As Single, meanq As Single
Dim InitQualMult As Single, TimePerMult As Single
Dim duration As Integer, TimetoAdd As Integer
```

```
InputFile = "C:\temp\THE_MICROPOLIS_MODELtoxic_sourcequal.inp"
ReportFile = "C:\temp\THEMODEL_G&BRep.txt"
BinaryFile = "C:\temp\THEMODEL_G&BBin.txt"
tstep = 10800

Randomize

NumIt = 15000
ProgCounter = 0

For j = 1 To NumIt
'   Open toolkit
    ENopen InputFile, ReportFile, ""
'   Retrieve total node count
    ENgetcount EN_NODECOUNT, NumNodes

'   1) UNCERTAINITY IN DAILY DEMANDS
    For m = 1 To NumNodes
        ENgetnodeid m, id
        If Left(id, 2) = "TN" Then
            For i = 1 To 24
                    ENgetpatternvalue m, i, mean
```

```
            adjmultiplier = NormRand(mean)

            ENsetpatternvalue m, i, adjmultiplier

        Next i

      End If

    Next m

'   2) UNCERTAINTY IN INITIAL TANK LEVELS

    InTankLevel = TankMCLognormGen()

    'ENgetnodeindex "Tank", Index

    ENsetnodevalue 1577, EN_TANKLEVEL, InTankLevel

'   3) UNCERTAINTY IN CONTAMINANT INITIATION TIME

'   Establish initiation time based on Beta(0.5,0.5) Distribution and A,B = 0,24 hours

    ContamInit = BetaRand()

'   4) UNCERTAINTY IN ARSENIC QUANITY OF INITIATION TIME PERIOD

    InitQualMult = LognormRand_Quantity()

    ENsetpatternvalue 7, ContamInit, InitQualMult

'   5) UNCERTAINTY IN CONTAMINANT INTRUSION DURATION

    duration = LognormRand_Duration()

    TimetoAdd = duration - 1
```

```
NextTimePer = ContamInit + 1

    If TimetoAdd > 0 Then
        For i = 1 To TimetoAdd
            ' setting arsenic QUANTITY MULTIPLIER for current time period
            TimePerMult = LognormRand_Quantity()
            ENsetpatternvalue 7, NextTimePer, TimePerMult
            NextTimePer = NextTimePer + 1
        Next i
    End If

'   6) UNCERTAINTY IN SEASONAL DEMANDS
    u = Round(Rnd(), 2)
    If u > 0.75 Then
        ElemDemand = 0
        MidDemand = 0
        HSDemand = 0
        ENsetnodevalue 364, EN_BASEDEMAND, ElemDemand
        ENsetnodevalue 468, EN_BASEDEMAND, MidDemand
        ENsetnodevalue 469, EN_BASEDEMAND, HSDemand
        Else:
        ElemDemand = 77.77777778
```

```
    MidDemand = 55.55555556
    HSDemand = 42.66666667
    ENsetnodevalue 364, EN_BASEDEMAND, ElemDemand
    ENsetnodevalue 468, EN_BASEDEMAND, MidDemand
    ENsetnodevalue 469, EN_BASEDEMAND, HSDemand
  End If
  ENsolveH
'  Open water quality solver
  ENopenQ
'  Intialize simulation and simulation clock
  ENinitQ 1

  Do
    ENrunQ t
     'Contamination event can only occur within first 24 hours, does not repeat itself
     ‘in day 2 or day 3
    If t > 86400 Then
      For i = 1 To 24
        ENsetpatternvalue 7, i, 0
      Next i
    End If
    If (t / 3600) - Int(t / 3600) = 0 Then
```

```
        Call write_time(t)
          For i = 1 To NumNodes
            ENgetnodevalue i, EN_BASEDEMAND, BDemand
            ENgetnodevalue i, EN_QUALITY, c
            If BDemand > 0 And c > 0 Then
              ENgetnodeid i, id
              ENgetnodevalue i, EN_PRESSURE, p
              ENgetnodevalue i, EN_DEMAND, d
              Call write_rest(id, p, d, c)
            End If
          Next i
        Call prep
      End If
      ENnextQ tstep
Loop Until t = 259200
Call GrabSeriesData
Call HistPrep
Call ClearOC
PctDone = (ProgCounter / NumIt)
Call UpdateProgress(PctDone)
ProgCounter = ProgCounter + 1
ENcloseQ
```

```
  ENclose
  Next j
  Unload UserForm1
End Sub

Sub write_time(t As Long)
'   This procedure gets called later to transfer data headers and the current time
'   Transfer all headers
    With ActiveCell
        .Value = "Time" & Chr(10) & "(sec)"
        .Offset(0, 1).Value = "Time" & Chr(10) & "(hrs)"
        .Offset(0, 2).Value = "Time" & Chr(10) & "(days)"
        .Offset(0, 3).Value = "Node ID"
        .Offset(0, 4).Value = "Pressure" & Chr(10) & "(psi)"
        .Offset(0, 5).Value = "Demand" & Chr(10) & "(gpm)"
        .Offset(0, 6).Value = "Toxicity" & Chr(10) & "(mg/L)"
        .Offset(0, 7).Value = "Pop"
        .Offset(1, 0).Activate
    End With

'   Transfer time step
    With ActiveCell
```

```
        .Value = t
        .Offset(0, 1).Value = t / 3600
        .Offset(0, 2).Value = t / 86400
    End With
    ActiveCell.Offset(0, 3).Activate
End Sub
```

Sub write_rest(id As String, p As Single, d As Single, c As Single)

```
'   This procedure is called later to write the Node ID, pressure, and concentration for the
current node
'   at the current time block.
'   Transfer argument values
    With ActiveCell
        .Value = id
        .Offset(0, 1).Value = p
        .Offset(0, 2).Value = d
        .Offset(0, 3).Value = c
        .Offset(0, 4).Value = Application.WorksheetFunction.VLookup(ActiveCell.Value,
Worksheets("Lookup").Range("A1:B686"), 2)
        .Offset(1, 0).Activate
    End With
End Sub
```

Sub prep()

```
'   This procedure is called later to format current time block and prep the next
Dim CurrentRow As Long, MCLPop As Long, LethPop As Long
Dim ActiveRow As Long, ActiveCol As Long
Dim NumberofRows As Long

    ActiveCell.Offset(-1, 0).Activate
    ActiveCell.CurrentRegion.Select

    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlTop
    End With

    ActiveCell.Offset(0, 7).Activate
    ActiveRow = ActiveCell.Row
    ActiveCol = ActiveCell.Column

    If ActiveCell.Offset(1, 0).Value = "" Then
        With ActiveCell
            .Offset(1, 0).Value = "none"
            .Offset(1, -1).Value = "none"
```

```
        .Offset(1, -2).Value = "none"
        .Offset(1, -3).Value = "none"
        .Offset(1, -4).Value = "none"
    End With
End If

ActiveCell.Offset(1, 1).Value = "Total Pop ="
ActiveCell.Offset(1, 2).Value = _
Application.WorksheetFunction.Sum(Range(Cells(ActiveRow, ActiveCol),
Cells(ActiveCell.End(xlDown).Row, ActiveCol)))
ActiveCell.Offset(2, 1).Value = "(>=0.010) ="
Range(Cells(ActiveRow, ActiveCol), Cells(ActiveCell.End(xlDown).Row, _
ActiveCol)).Select
NumberofRows = Selection.Rows.Count - 1
ActiveCell.Offset(1, -1).Activate
MCLPop = 0
For i = 1 To NumberofRows
    If IsNumeric(ActiveCell.Value) = True And ActiveCell.Value > 0.01 Then
        MCLPop = MCLPop + ActiveCell.Offset(0, 1).Value
    End If
    ActiveCell.Offset(1, 0).Activate
Next i
```

```
    ActiveCell.Offset(-1, 0).Activate
    ActiveCell.End(xlUp).Activate
    ActiveCell.Offset(2, 3).Value = MCLPop
    ActiveCell.Offset(3, 2).Value = "(>=5) ="
    ActiveCell.Offset(1, 0).Activate
    LethPop = 0
    For i = 1 To NumberofRows
        If IsNumeric(ActiveCell.Value) = True And ActiveCell.Value > 5 Then
            LethPop = LethPop + ActiveCell.Offset(0, 1).Value
        End If
        ActiveCell.Offset(1, 0).Activate
    Next i
    ActiveCell.Offset(-1, 0).Activate
    ActiveCell.End(xlUp).Activate
    ActiveCell.Offset(3, 3).Value = LethPop
    Range(Cells(ActiveRow, ActiveCol), Cells(ActiveCell.End(xlDown).Row, _
    ActiveCol)).Select
    If Selection.Rows.Count < 4 Then
        ActiveCell.Offset(7, -7).Activate
        Else: ActiveCell.End(xlDown).Offset(4, -7).Activate
    End If
End Sub
```

```
Sub UpdateProgress(Pct)
'   This procedure is for the progress bar that gets displayed
    With UserForm1
        .FrameProgress.Caption = Format(Pct, "0%")
        .LabelProgress.Width = Pct * (.FrameProgress.Width - 10)
        .Repaint
    End With
End Sub


Sub ShowDialog()
'   This procedure initiates the progress bar
    Worksheets("Output").Activate
    ActiveWindow.WindowState = xlMinimized
    Range("A1").Activate
    UserForm1.LabelProgress.Width = 0
    UserForm1.Show
    ActiveWindow.WindowState = xlMaximized
End Sub


Sub GrabSeriesData()
'   This procedure gets called later.
'   Part 1 of 2 used to help write the output for number exposed used to create histogram
```

```
Dim timex As Long, popul As Long, Mpop As Long, Lpop As Long

    Worksheets("Output").Activate
    Range("B2").Activate
    Do
        timex = ActiveCell.Value
        popul = ActiveCell.Offset(0, 8).Value
        Mpop = ActiveCell.Offset(1, 8).Value
        Lpop = ActiveCell.Offset(2, 8).Value

        Call NextRowPro(timex, popul, Mpop, Lpop)


        Worksheets("Output").Activate
        ActiveCell.End(xlDown).Activate
        ActiveCell.Offset(1, 0).Activate
    Loop Until ActiveCell.Value = 72
    timex = ActiveCell.Value
    popul = ActiveCell.Offset(0, 8).Value
    Mpop = ActiveCell.Offset(1, 8).Value
    Lpop = ActiveCell.Offset(2, 8).Value
    Call NextRowPro(timex, popul, Mpop, Lpop)
End Sub
```

```
Sub NextRowPro(timex As Long, popul As Long, Mpop As Long, Lpop As Long)
'   This procedure gets called later.
'   It is part 2 of 2 used to help write the output for number exposed used to create a histogram
Dim NextRow As Long

    Worksheets("Chart").Activate
    Range("A1").Value = "Time"
    Range("B1").Value = "Pop"
    Range("C1").Value = "(>=0.010)"
    Range("D1").Value = "(>=5)"
    NextRow = Application.WorksheetFunction.CountA(Range("A:A")) + 1
    Cells(NextRow, 1).Activate
    ActiveCell.Value = timex
    ActiveCell.Offset(0, 1).Value = popul
    ActiveCell.Offset(0, 2).Value = Mpop
    ActiveCell.Offset(0, 3).Value = Lpop
End Sub

Sub HistPrep()
'   This procedure gets called later.
'   It is used to help write the input range needed to create the histogram.
```

```
Dim MCLexp As Single, Letexp As Single, NextRecord As Single

    MCLexp = Application.WorksheetFunction.Max(Range("C2:C74"))
    Letexp = Application.WorksheetFunction.Max(Range("D2:D74"))

    Worksheets("Hist").Activate
    NextRecord = Application.WorksheetFunction.CountA(Range("B:B")) + 1
    Cells(NextRecord, 2).Value = MCLexp
    Cells(NextRecord, 4).Value = Letexp
End Sub

Sub ClearOC()
'   This procedure gets called later to clear the "Output" and "Chart" worksheets
'   for next iteration.
    Worksheets("Output").Activate
    Worksheets("Output").Cells.Select
    Selection.ClearContents
    Worksheets("Output").Range("A1").Select
    Worksheets("Chart").Activate
    Worksheets("Chart").Cells.Select
    Selection.ClearContents
    Worksheets("Chart").Range("A1").Select
```

```
    Worksheets("Output").Activate

    Range("A1").Activate

End Sub
```

Function Procedures

```
Option Explicit


Function NormRand(mean As Single) As Single
'   Used for daily demands
Dim Value1 As Single, Value2 As Single, Fac As Single, Rsq As Single, stdev _
 As Single
   Randomize
   Do
      Value1 = 2 * Rnd - 1
      Value2 = 2 * Rnd - 1
      Rsq = Value1 ^ 2 + Value2 ^ 2
   Loop Until Rsq > 0 And Rsq < 1
   Fac = (-2 * Log(Rsq) / Rsq) ^ 0.5
   stdev = 0.25 * mean
   If Rnd < 0.5 Then
      NormRand = (Value1 * Fac) * stdev + mean
   Else
      NormRand = (Value2 * Fac) * stdev + mean
   End If
End Function
```

```
Function TankMCLognormGen() As Single
'   Used for Initial Tank Level
        'TankMCLognormGen = Exp(WhiteNoise * stdev(ln(x)) + mean(ln(x)))
        TankMCLognormGen = Exp((WhiteNoise * 0.016) + 4.693)
        TankMCLognormGen = Round(TankMCLognormGen, 2)
End Function


Function BetaRand() As Double
'   Used for Initiation Time.  Generates a Beta distribution random number with
‘  parameters alpha, beta, A, and B.
    Do
        BetaRand = Round(WorksheetFunction.BetaInv(alea(), 0.5, 0.5, 0, 25), 0)
    Loop Until BetaRand <> 0 And BetaRand <> 25
End Function


Function LognormRand_Quantity() As Single
'   Used for Arsenic Quantity
Dim Value1 As Single, Value2 As Single, Fac As Single, Rsq As Single, stdev As
Single
    Randomize
    Do
        Value1 = 2 * Rnd - 1
```

```
    Value2 = 2 * Rnd - 1
    Rsq = Value1 ^ 2 + Value2 ^ 2
  Loop Until Rsq > 0 And Rsq < 1
  Fac = (-2 * Log(Rsq) / Rsq) ^ 0.5
    mean = -0.16841
  stdev = 0.6417
  If Rnd < 0.5 Then
    LognormRand_Quantity = Exp((Value1 * Fac) * stdev + mean)
  Else
    LognormRand_Quantity = Exp((Value2 * Fac) * stdev + mean)
  End If
End Function


Function LognormRand_Duration() As Double
'  Used for contamination duration
    'ActiveCell(i) = Exp(WhiteNoise * stdev(ln(x)) + mean(ln(x)))
    LognormRand_Duration = Round(Exp((WhiteNoise * 0.392) + 0.672), 0)
    If LognormRand_Duration < 1 Then
      LognormRand_Duration = 0
    End If
End Function
```

```
Function WhiteNoise() As Single
'   Written by Kelly Brumbelow, Dept. of Civil Engineering, Texas A&M University.
'   Returns a normally distributed random variant with mean 0 and variance 1.
Dim Value1 As Single, Value2 As Single, Fac As Single, Rsq As Single
    Randomize
    Do
        Value1 = 2 * Rnd - 1
        Value2 = 2 * Rnd - 1
        Rsq = Value1 ^ 2 + Value2 ^ 2
    Loop Until Rsq > 0 And Rsq < 1
    Fac = (-2 * Log(Rsq) / Rsq) ^ 0.5
    If Rnd < 0.5 Then
        WhiteNoise = Value1 * Fac
    Else
        WhiteNoise = Value2 * Fac
    End If
End Function


Function alea()
'   This function is used to simulate uniformly distributed random variables [0 1]
‘   excluding ‘ 0 and 1.
Randomize
```

```
    alea = Rnd()
    If alea = 1 Then
        alea = 0.999999999999
    End If
    If alea = 0 Then
        alea = 1 - 0.999999999999
    End If
End Function
```

VITA

Jacob Manuel Torres was born in Corpus Christi, TX, and grew up in the small town of George West, Texas. He graduated from George West High School in 2001, and moved to College Station in 2002 to begin his studies at Texas A&M University. Jacob received a Bachelor of Science in Civil Engineering in 2006 and a Master of Science in Civil Engineering in 2008. His academic focus is in water resources engineering, and his research interests include water distribution system modeling, risk analysis, and uncertainty propagation.

Jacob's graduate studies have been supported by the TAMUS-Louis Stokes Alliance for Minority Participation (LSAMP) Bridge to the Doctorate Fellowship, a program funded by the National Science Foundation (NSF), and administered by the Texas A&M University System (TAMUS). Jacob has had the opportunity to intern with Lockwood, Andrews, and Newnam, Inc. (Summer 2006), CH2M Hill Hanford Group, Inc. (Summer 2004), and the U.S. Department of Energy (Summer 2003). He has also worked as a Teaching Assistant for Duke University's Talent Identification Program (Summer 2007).

Jacob can be reached by e-mail at jato@tamu.edu, or by contacting Dr. Kelly Brumbelow at Zachry Department of Civil Engineering, WERC Building, Room 205L, 3136 TAMU, College Station, TX 77843-3136.